Fast localization of coalescing binaries with gravitational wave detectors

and

Low frequency vibration isolation for KAGRA

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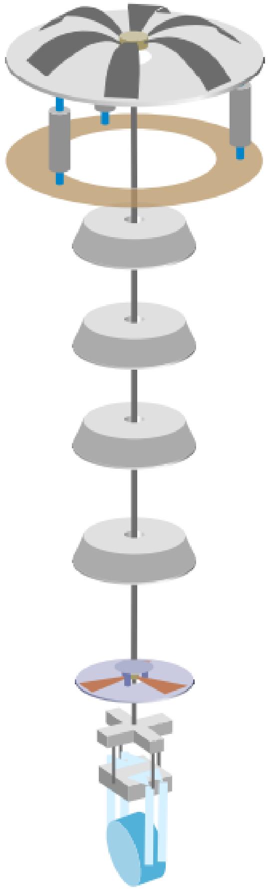


Abstract

1. Expected fast localization performance by current network with a hierarchical approach using existing low-latency infrastructure
   * In heterogeneous HLV-, HLK- and HLVK-network
   * If V (K) sensitivity > 0.2 (0.28) of LIGO, the hierarchical approach improves the localization performance, in the heterogeneous network using existing low-latency pipeline.

2. Local control system for KAGRA full Type-A suspension aiming more robust interferometer operation
   * I've confirmed the control system satisfied the requirements for acquiring interferometer lock.
   * This is the first time to control the KAGRA full Type-A suspension.

Thesis contents

My main research

1. Introduction
2. Benefit of adding detectors to the observation network
3. Low frequency vibration isolation
4. KAGRA seismic attenuation system
5. Suspension control design
6. Performance test of local control for KAGRA Type-A suspension
7. Summary

→ **Fast localization simulation with current network**

→ **Type-A suspension controls toward lock acquisition**

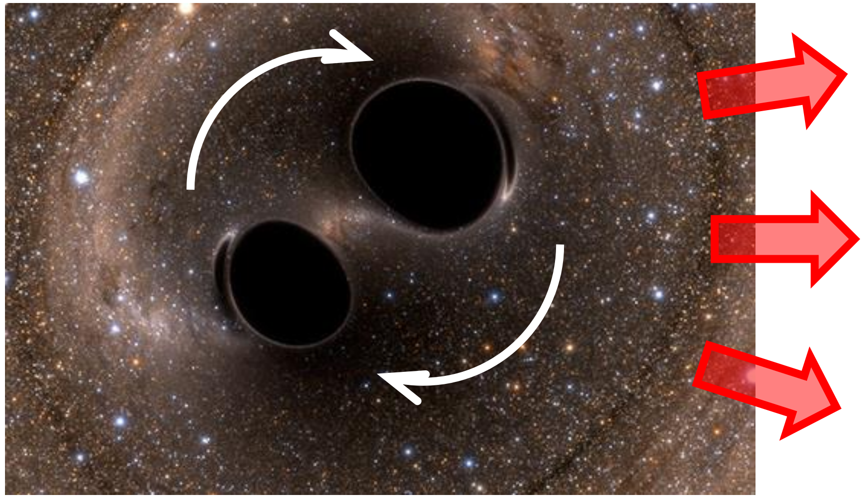
Introduction for my research topic:

Gravitational waves

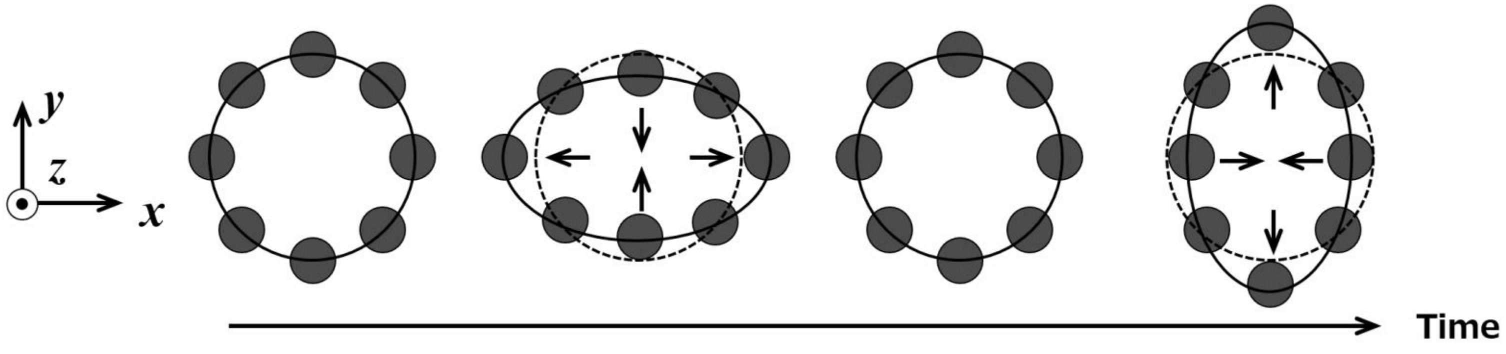
The sources

Detector, detection and source localization

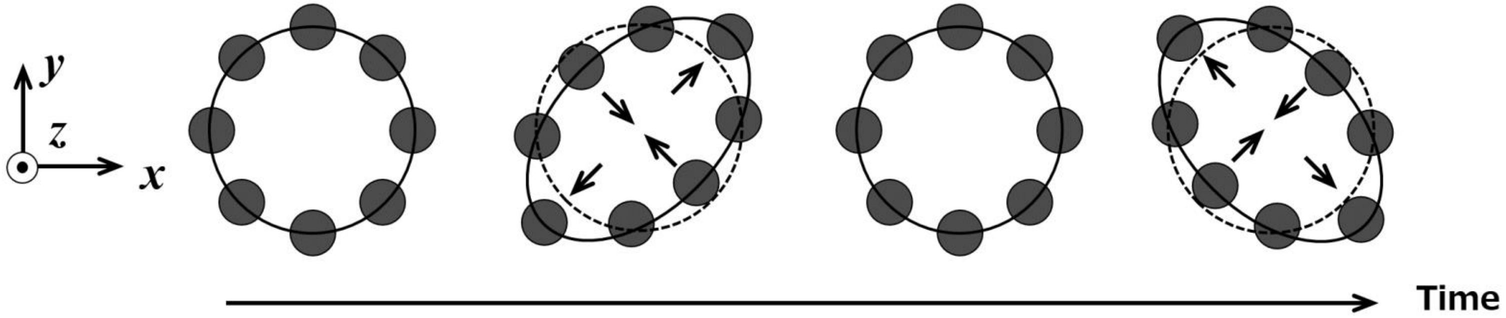
Gravitational wave (GW):



Plus mode



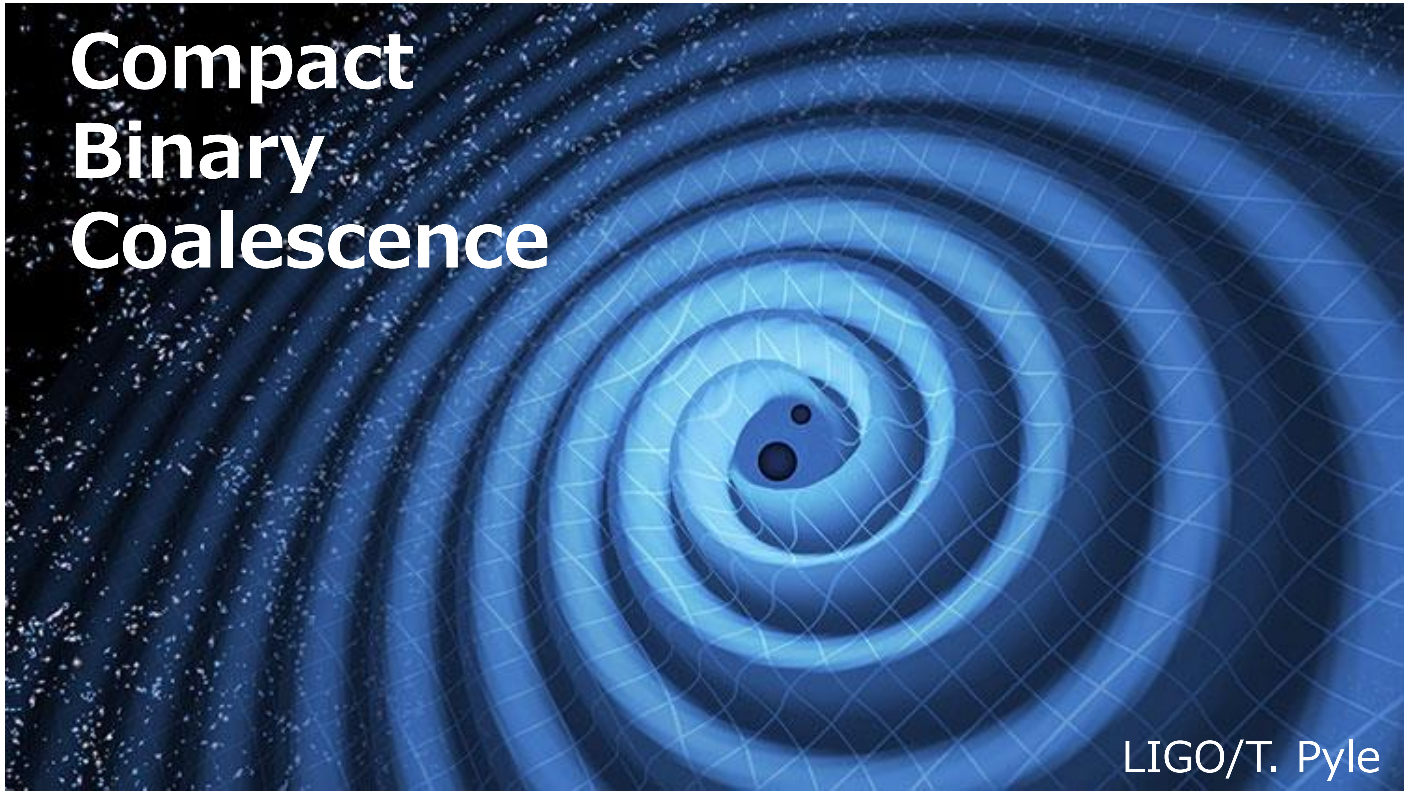
Cross mode

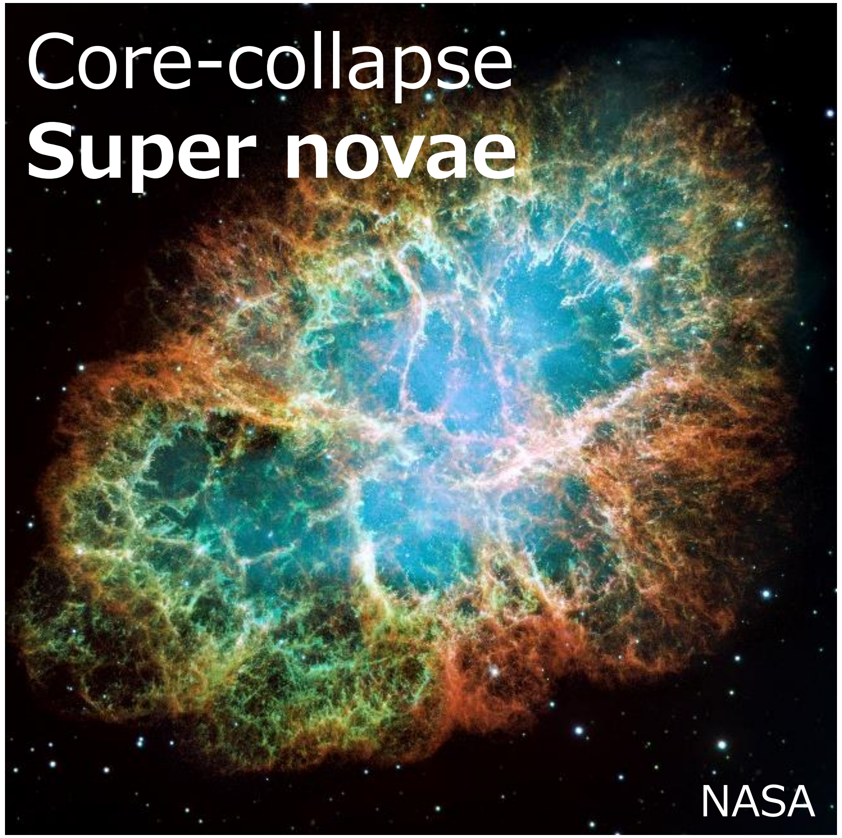


Accelerated objects generate GWs.

2 polarizations

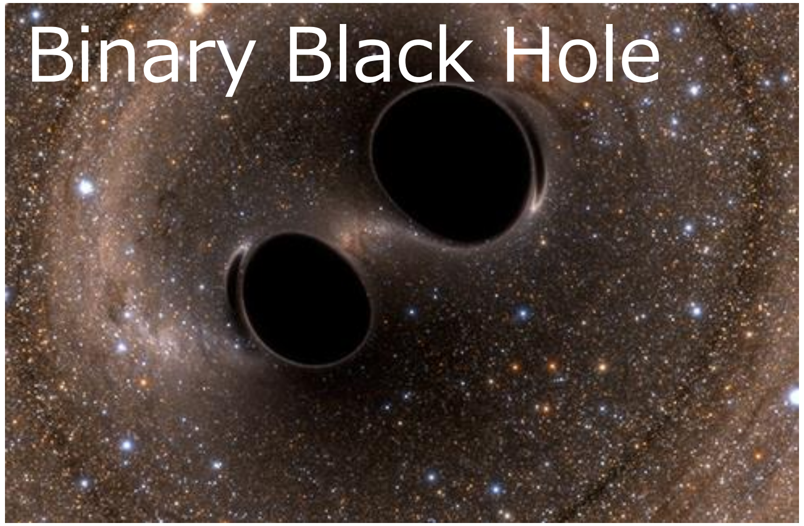
Promising sources of GW:





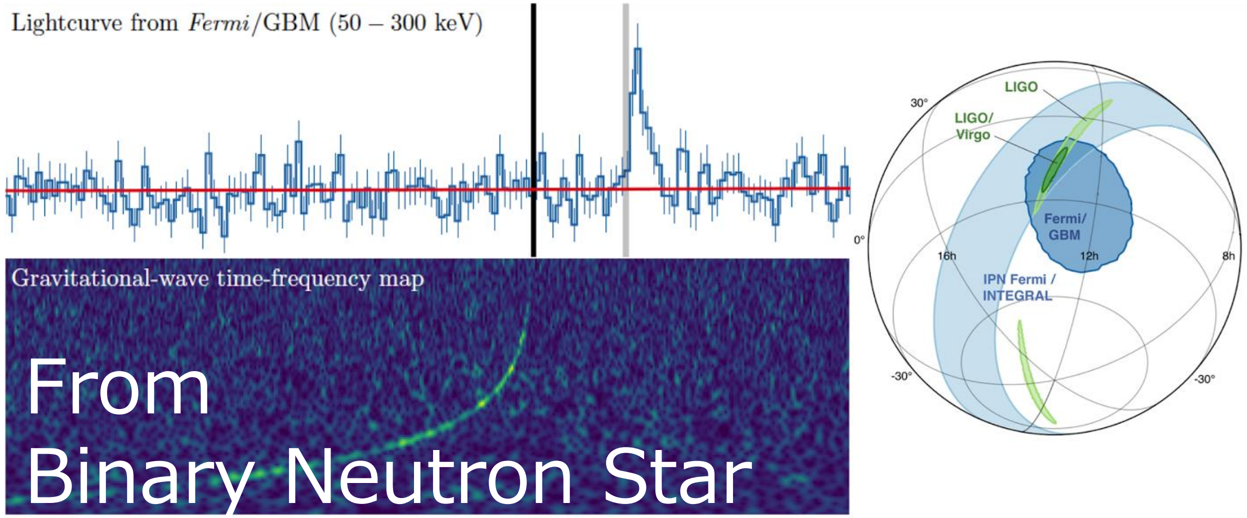
(And more..)

From CBC, GWs are detected:



* First BBH detection (2015)

→ **New field of astrophysics**

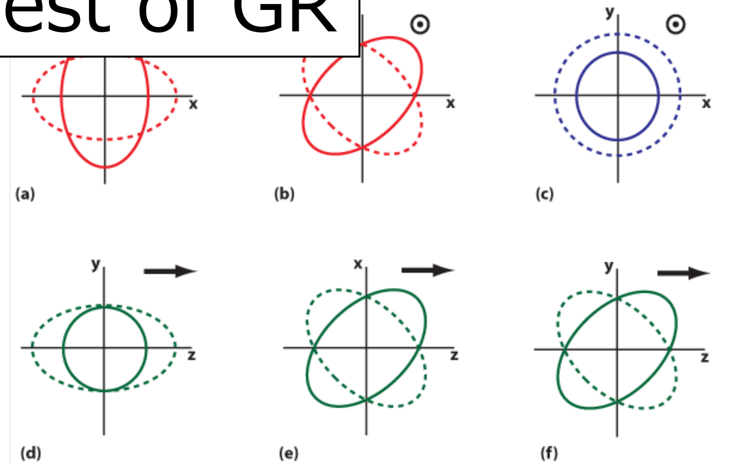


* First BNS detection &
EM-follow up (2017)

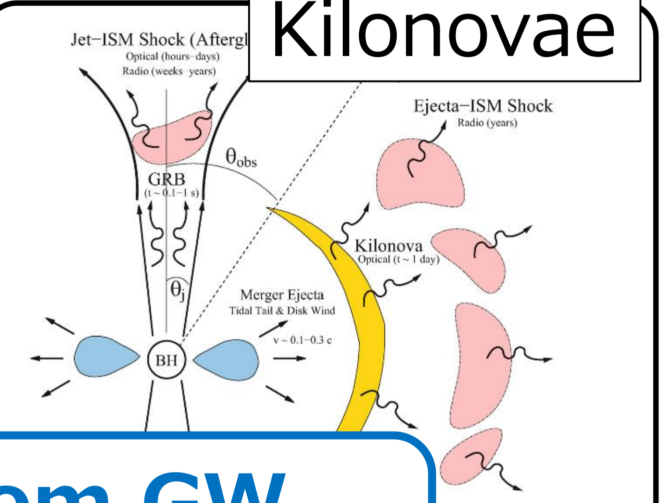
→ **Era of Multi-messenger astronomy**

Astrophysical motivation:

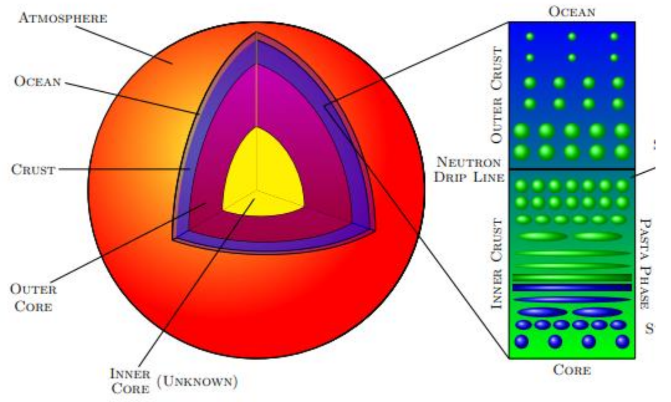
Test of GR



Kilonovae

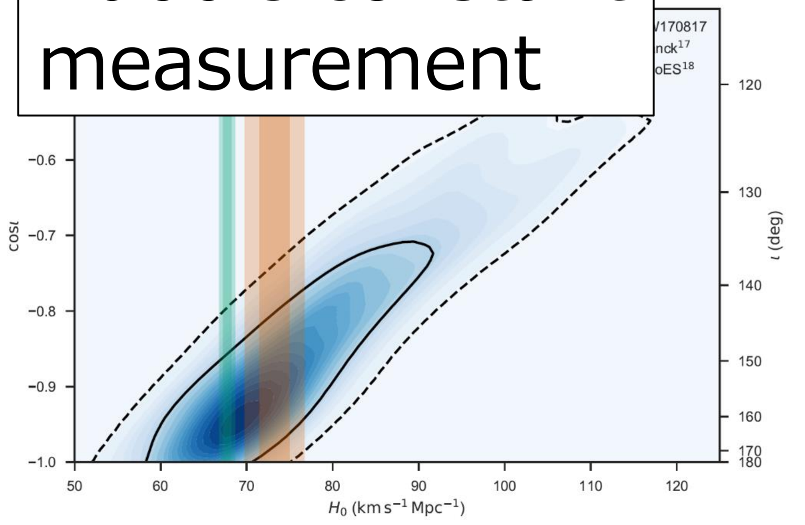


Neutron Star interior

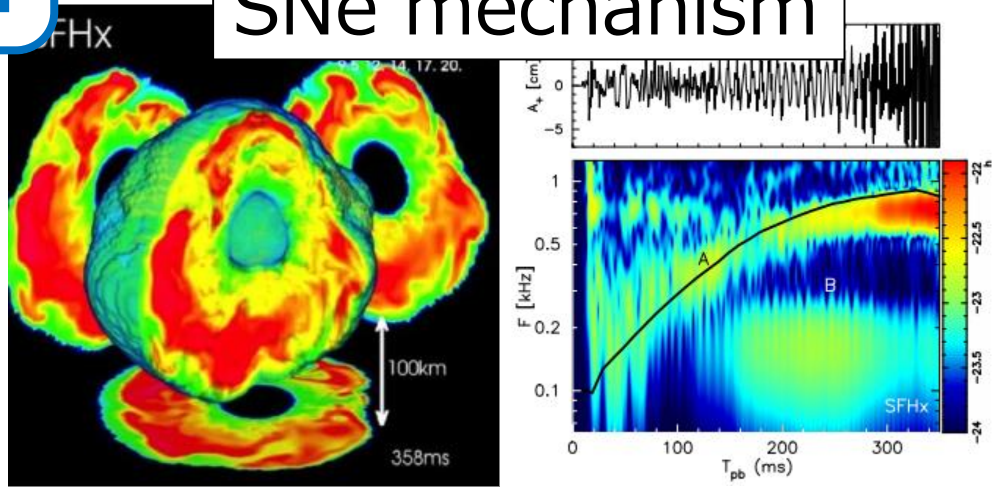


From GW observation

Hubble constant measurement

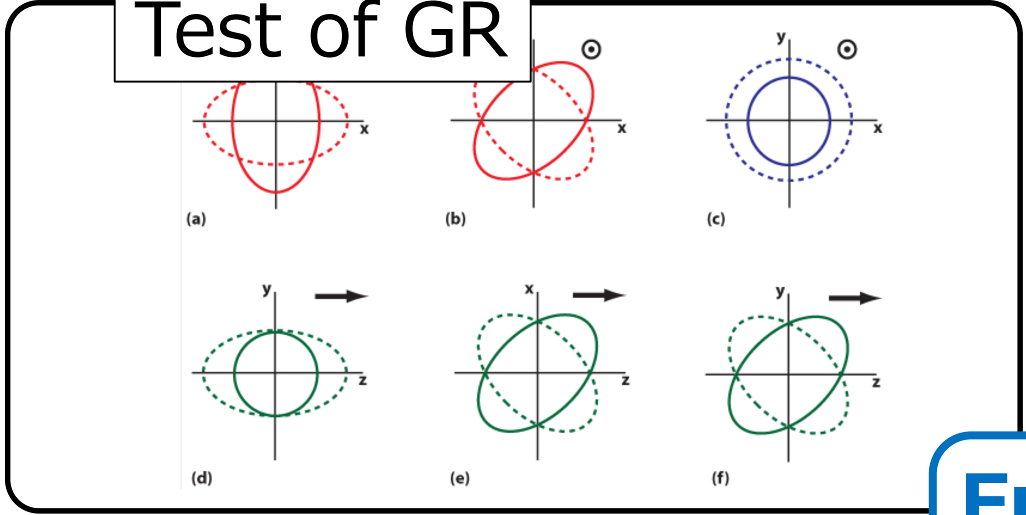


SNe mechanism

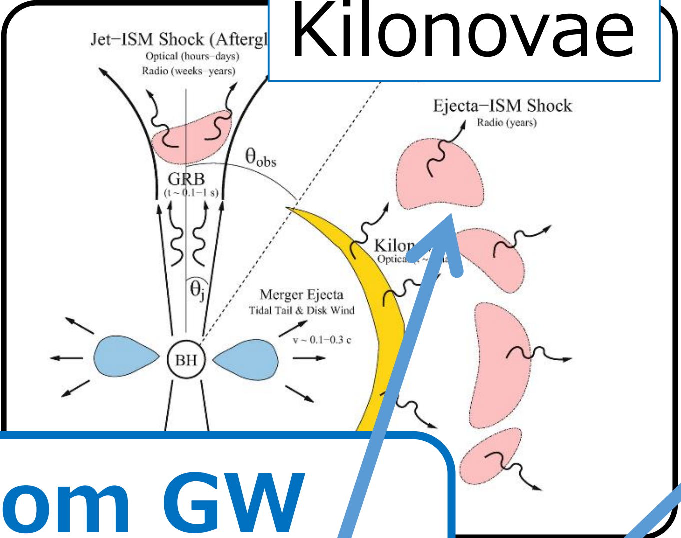


Astrophysical motivation:

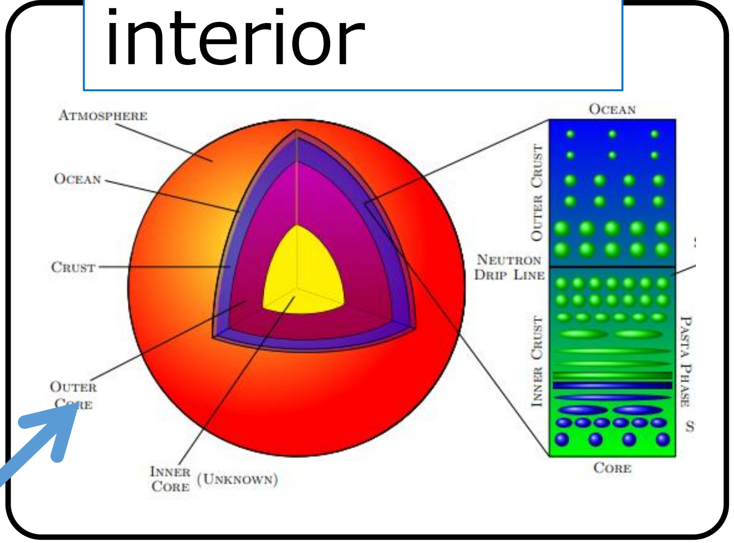
Test of GR



Kilonovae

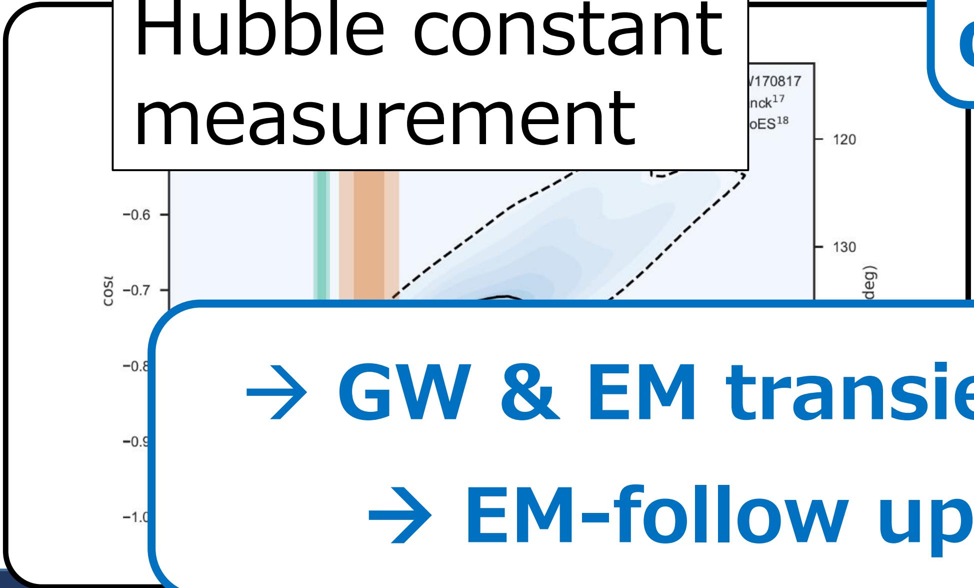


Neutron Star interior

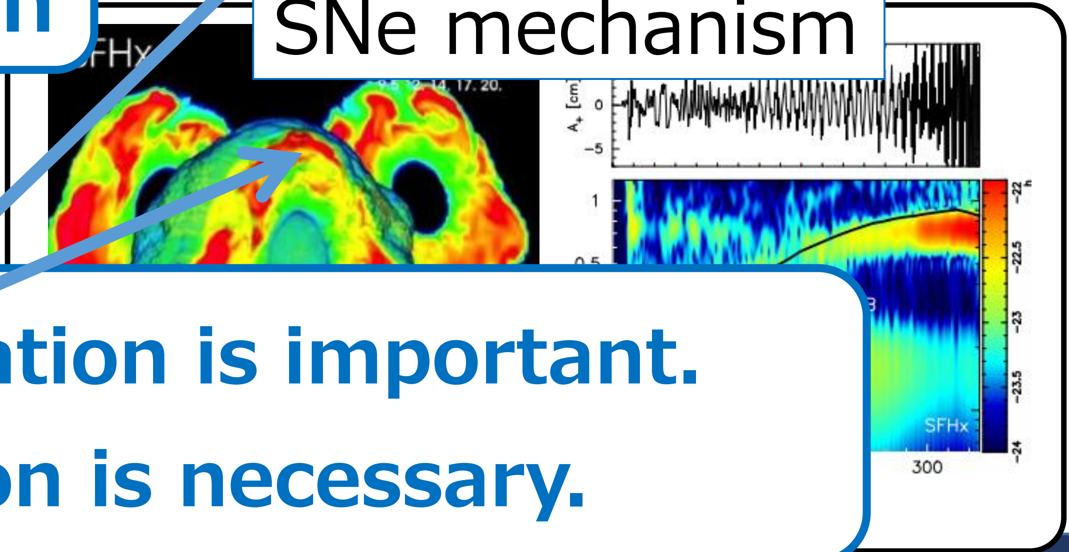


From GW observation

Hubble constant measurement



SNe mechanism

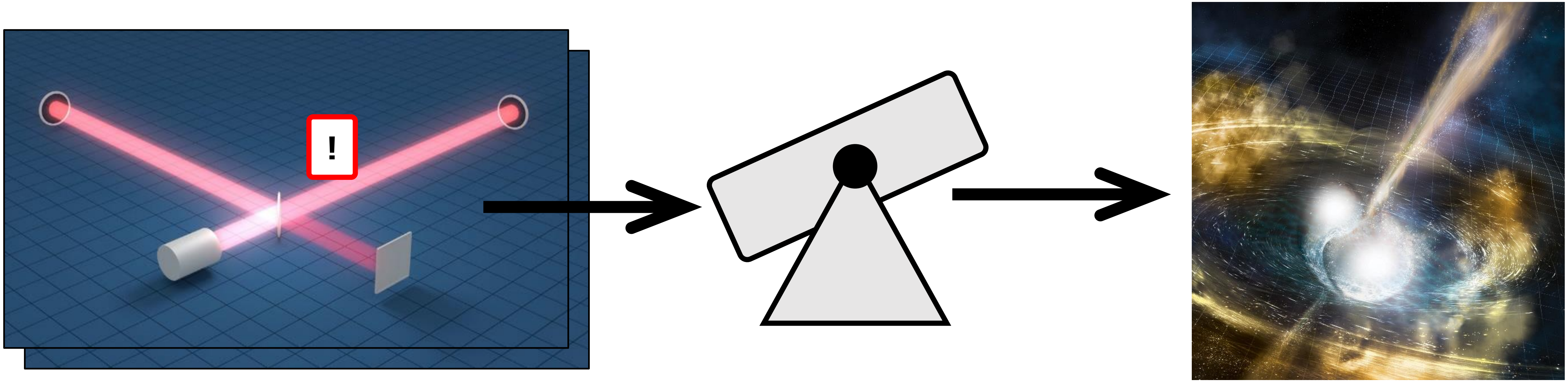


→ GW & EM transient observation is important.

→ EM-follow up observation is necessary.

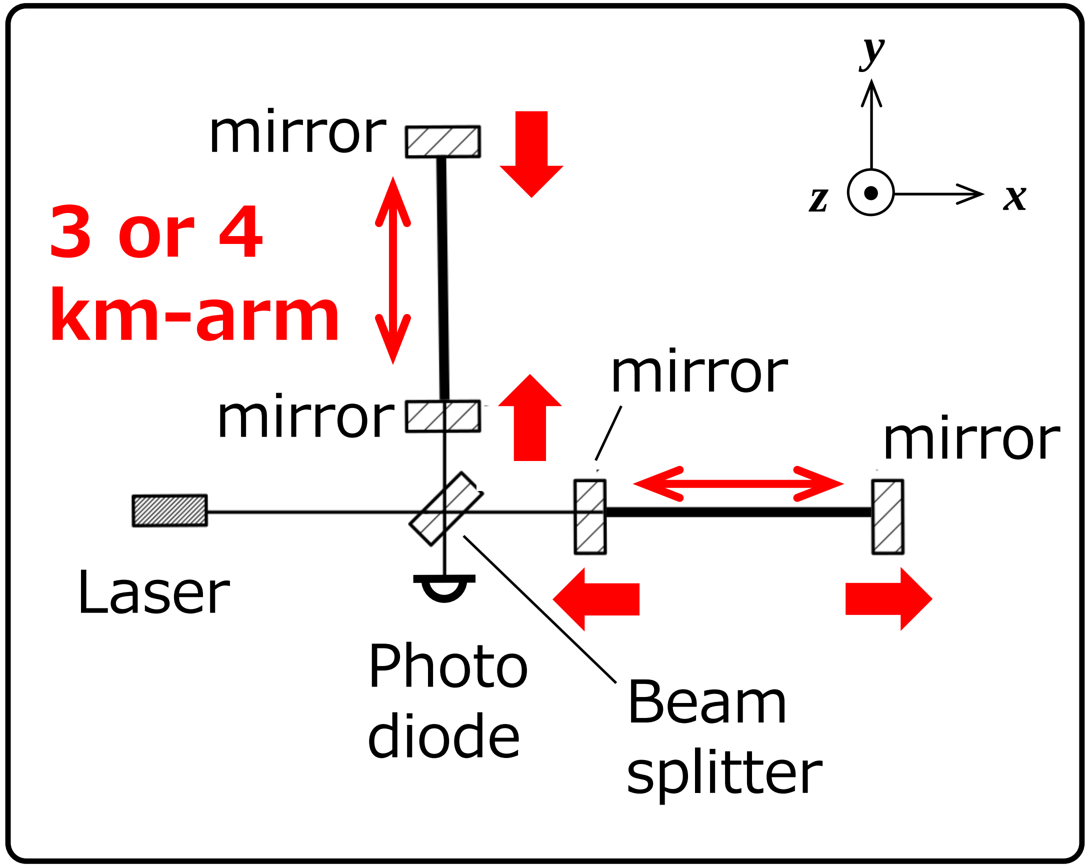
For effective EM-follow up observation

→ Fast source localization

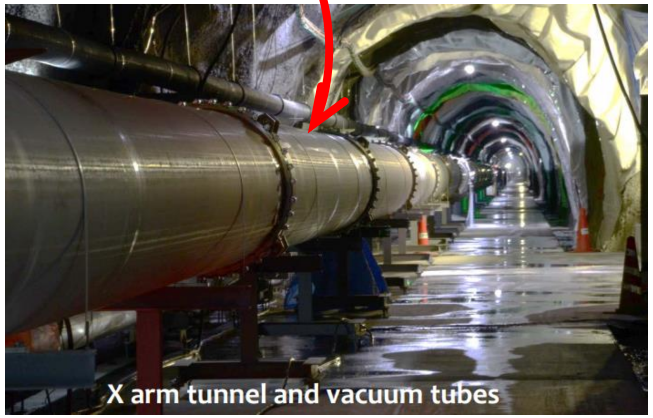


→ Topic for 1st part

GW detectors:



1) Based on Michelson interferometer
2) Optical cavities (Fabry-Perot cavities)
3) 3 or 4 km-arm



4) Suspended core optics

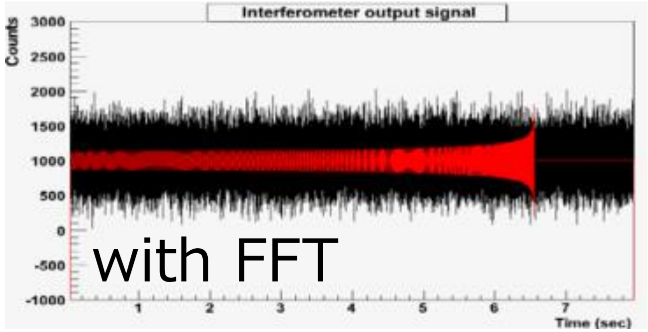
→ **Topic for 2nd part**

(Details → later)

Analysis for GW signals:

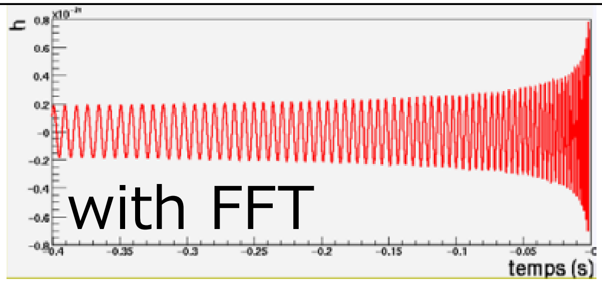
→ Matched filtering, for

Detector output

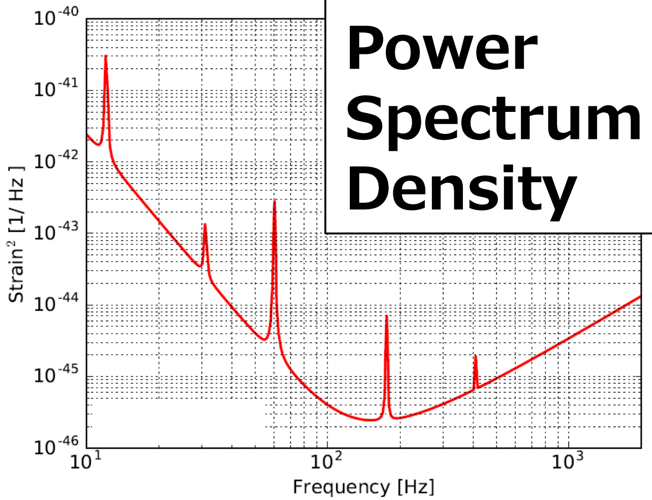


×

*Theoretical waveform (Template)

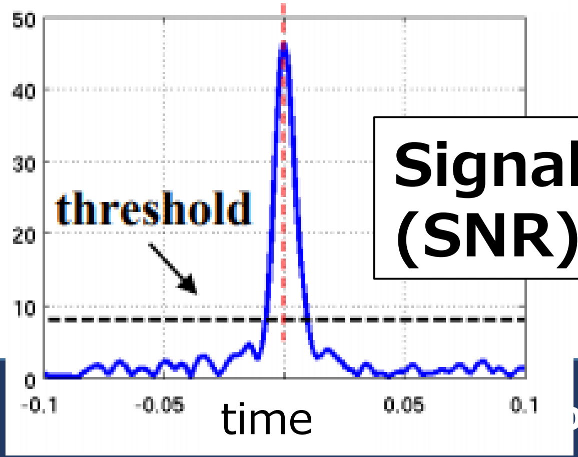


/



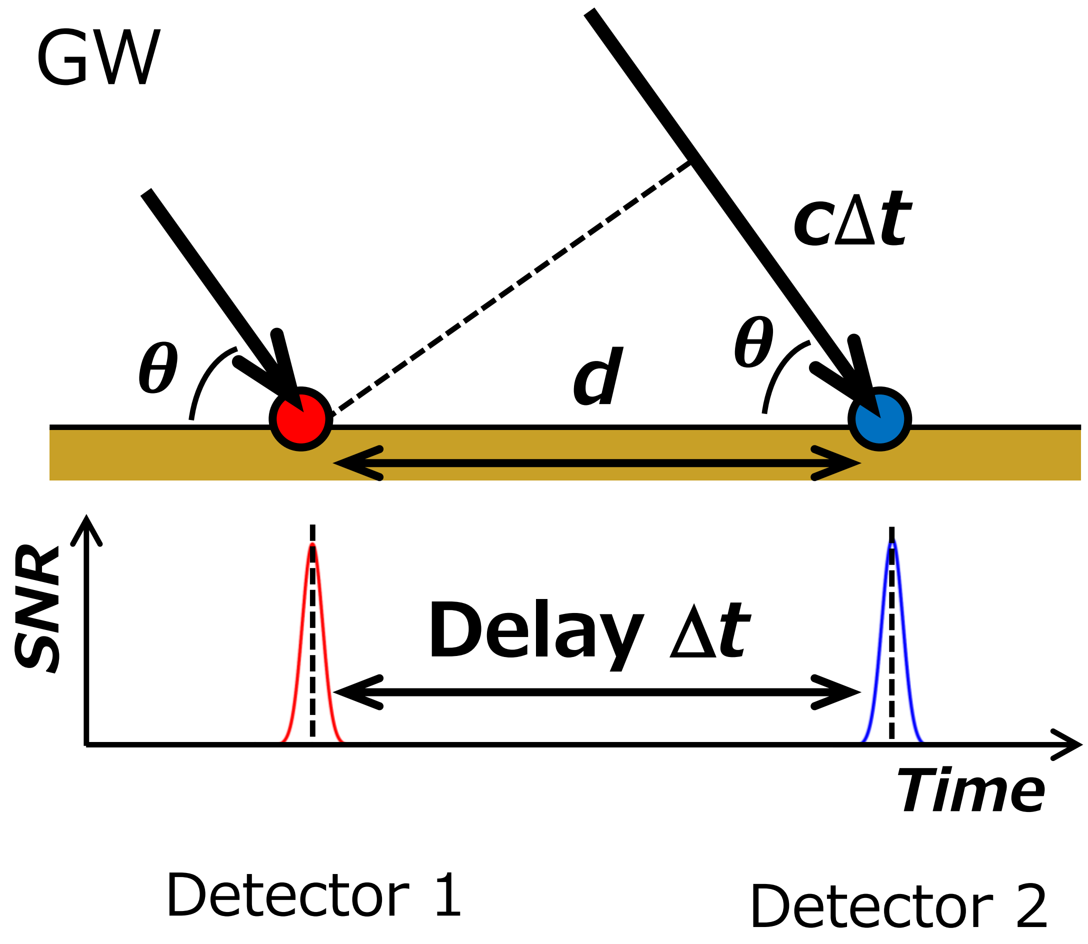
Noise Power Spectrum Density

→

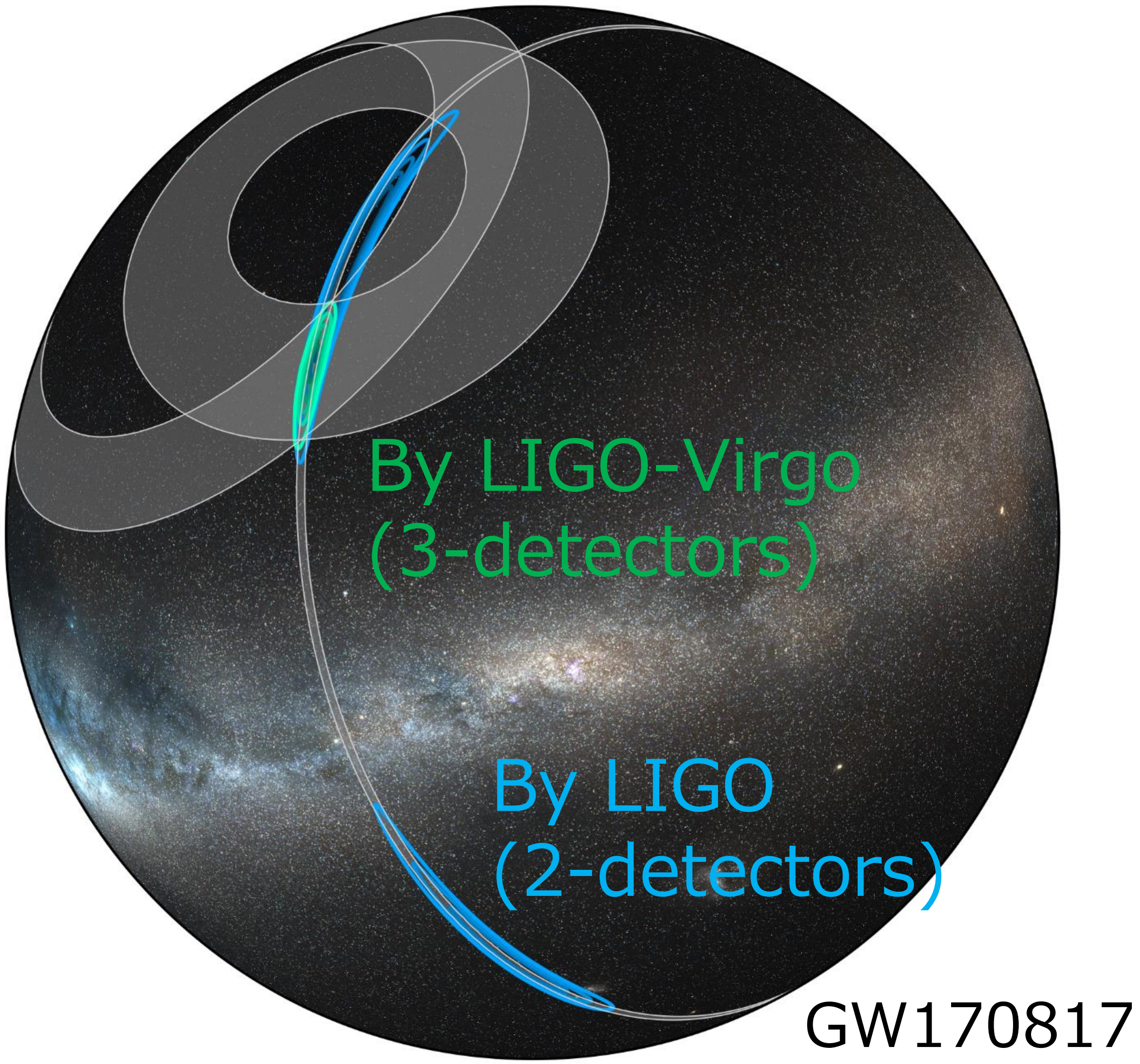


Signal-to-Noise ratio (SNR)

Source localization:

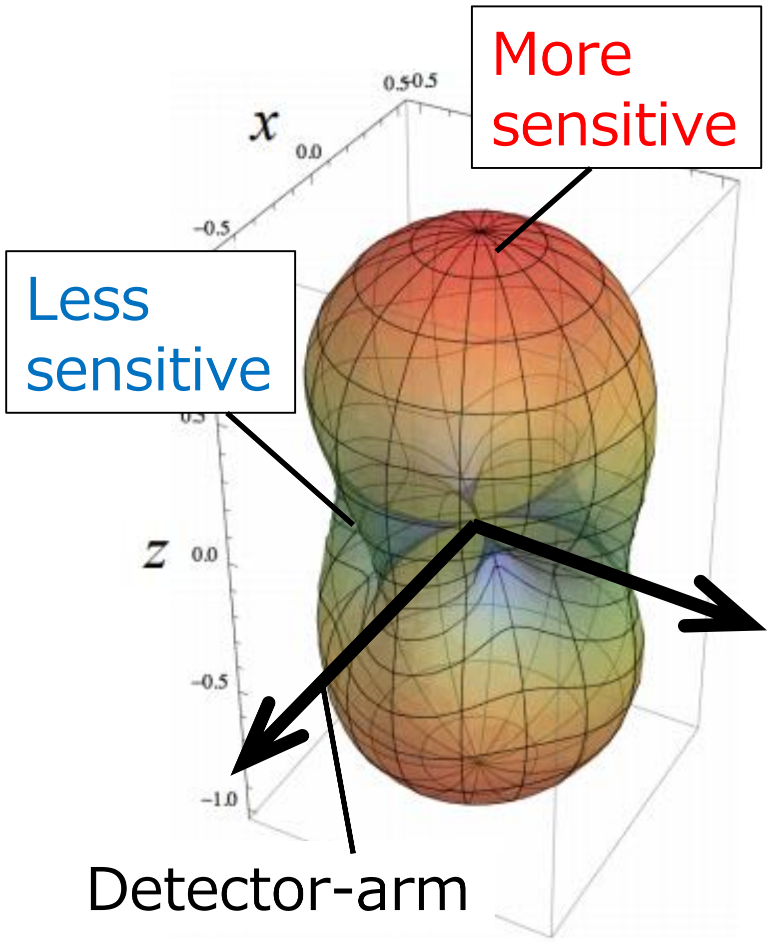


By 3-detector network :

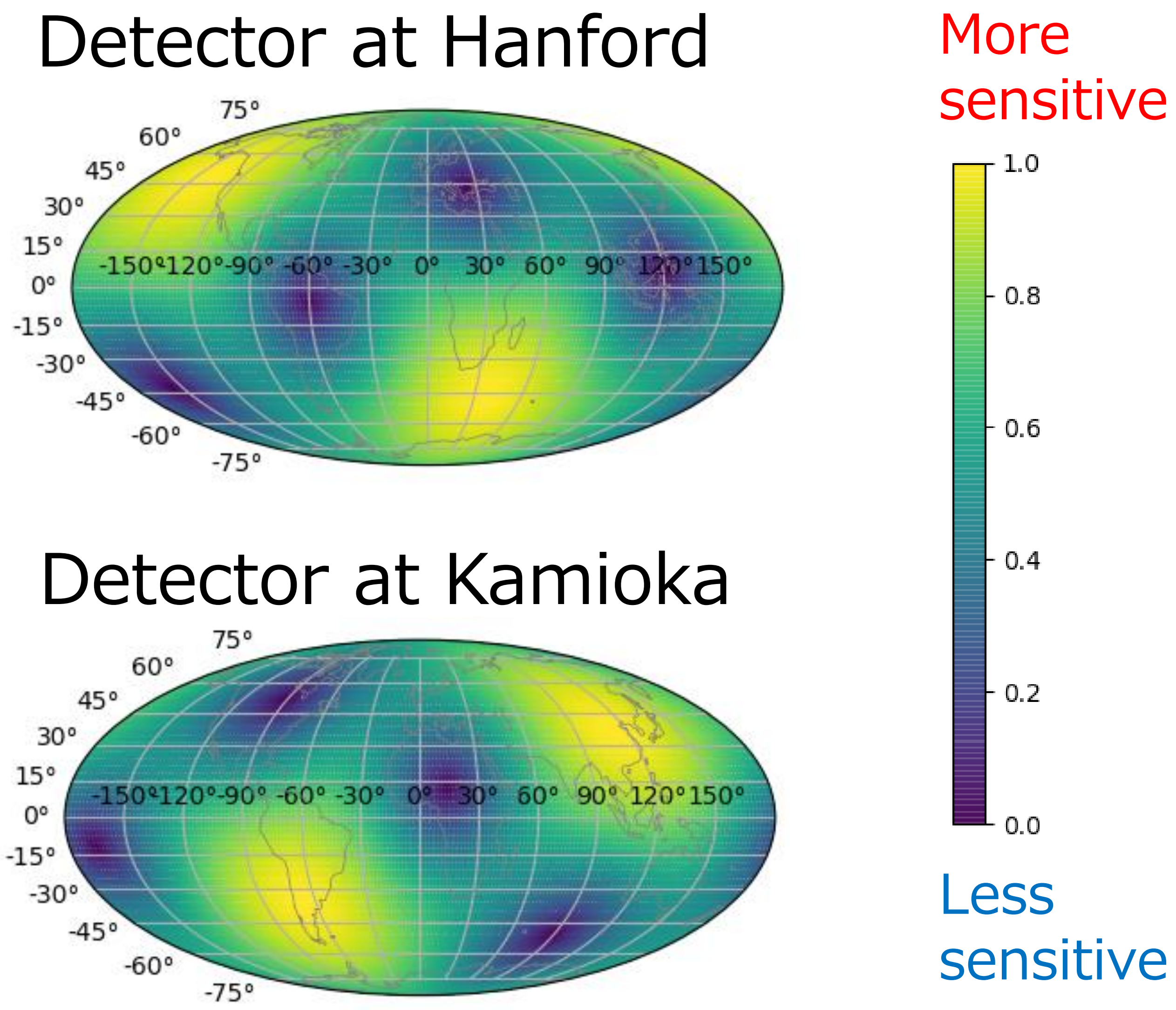


Credit: LIGO/Virgo/NASA/Leo Singer (Milky Way image: Axel Mellinger)

Antenna pattern of GW detector:

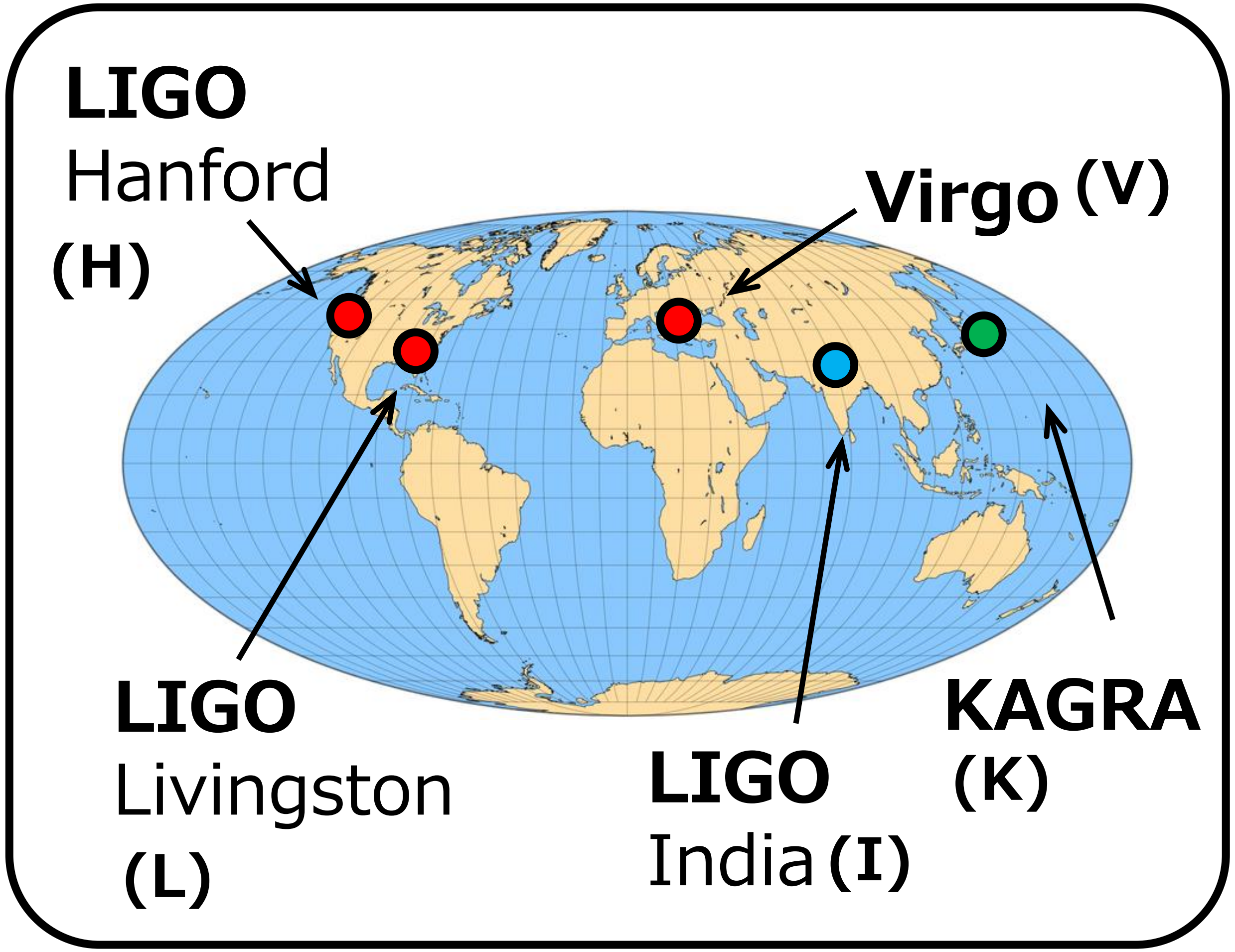


JGW-P1707567



Network by multiple GW detectors:

→ We are now building the network.



Multiple detectors will help:

* Better sky coverage
* More precise localization
* Higher network duty cycle

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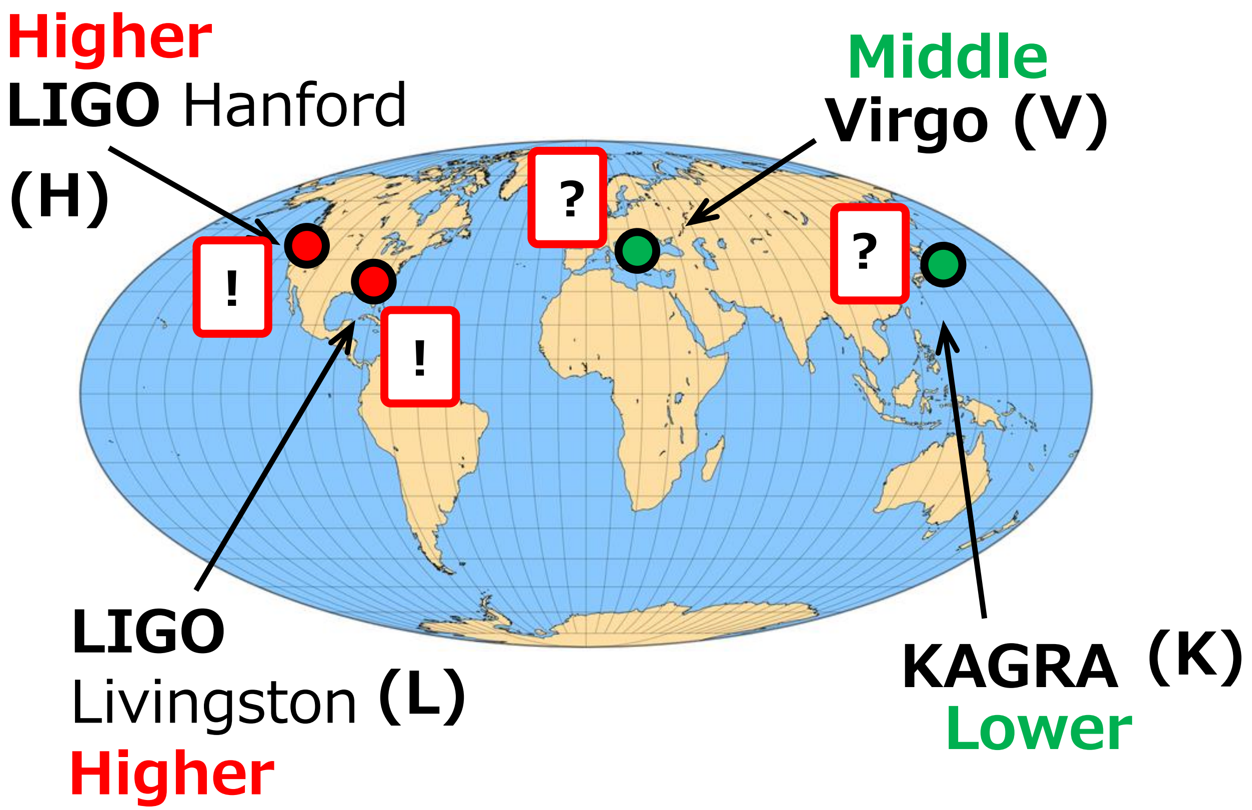
7. Summary

In heterogeneous network:



(At the beginning)

Ex.) SNR > SNRth → detection

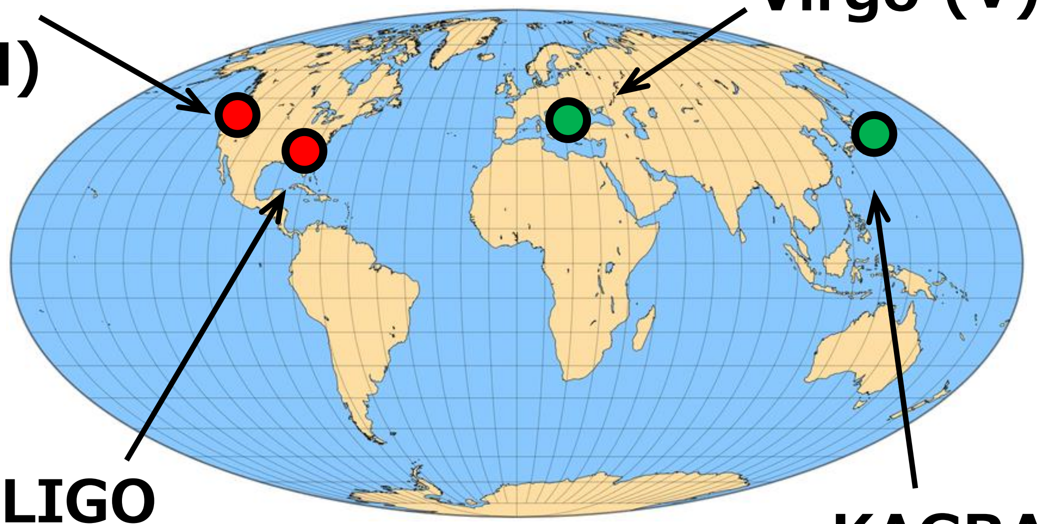
→ Triple (or more) coincidences
→ Hardly happens

→ Not good for EM-follow up

Indeed,
the real alert during O3:

~120 Mpc
LIGO Hanford
(H)

~ 45 Mpc
Virgo (V)

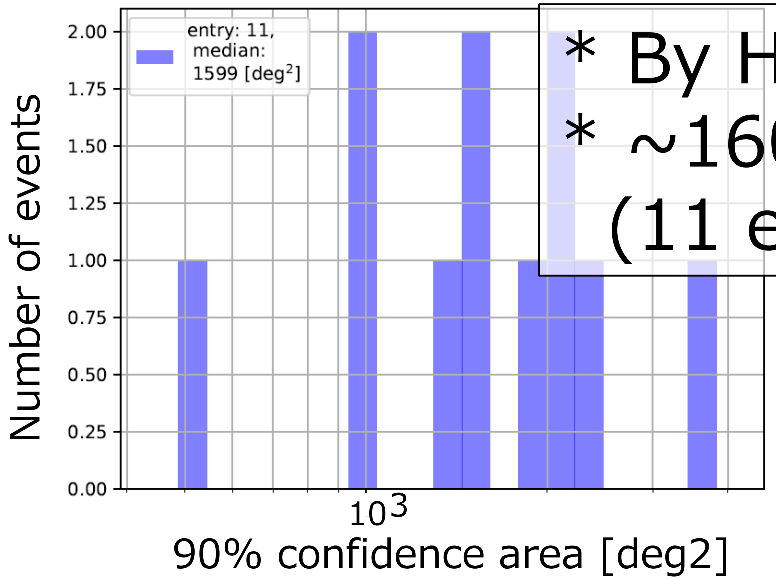


LIGO
Livingston **(L)**
~ 140 Mpc

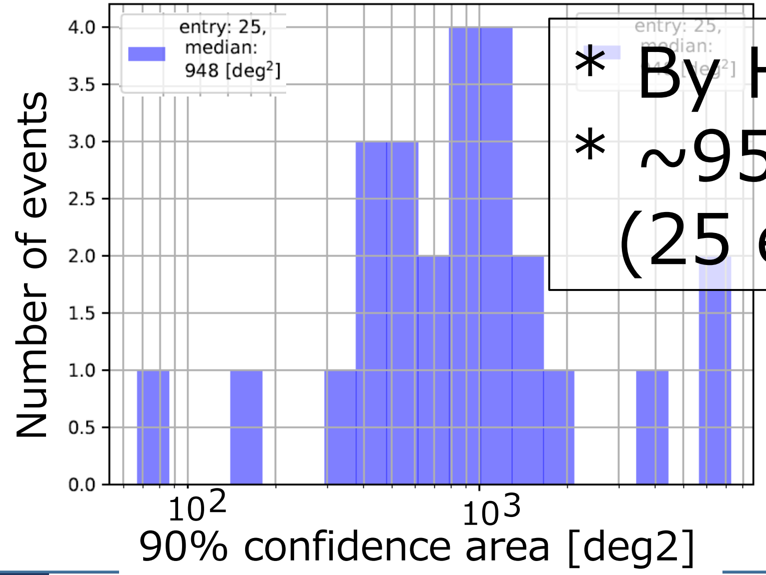
KAGRA
Being
commissioned

[ref] https://summary.ligo.org/~detchar/summary/O3a/

Size of localized area



* By HL
* ~1600 deg^2
(11 events)



* By HLV
* ~950 deg^2
(25 events)

[ref] https://gracedb.ligo.org/superevents/public/O3/

Demanded for EM-follow up:

As an example:

* For kilonova search with BlackGEM

→ **2.7 deg^2 / 5 min**
(for 23rd Magnitude)

[ref] https://link.springer.com/chapter/10.1007/978-3-319-10488-1_5

https://astro.ru.nl/blackgem/

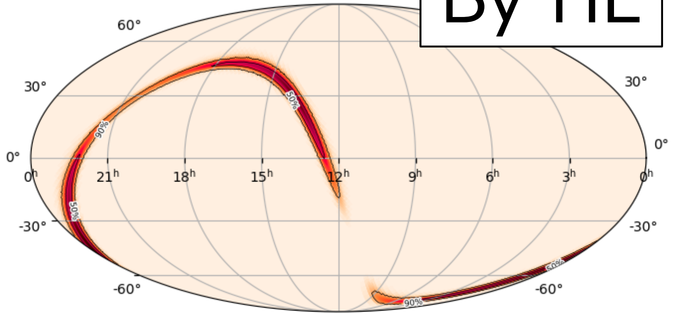
For 1600 deg^2, it will take ~50 hrs.

↓

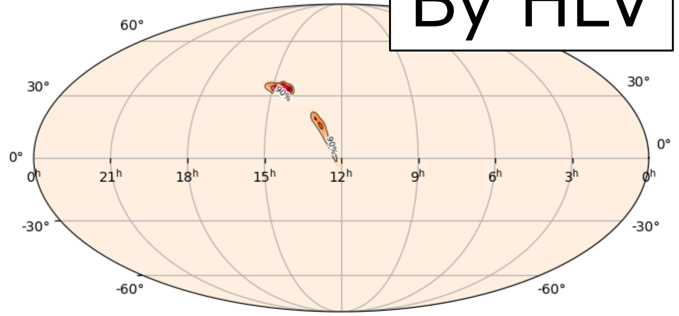
To complete < 9 hrs (one night)
→ < 300 deg^2

→ More than 3 detectors necessary.

By HL

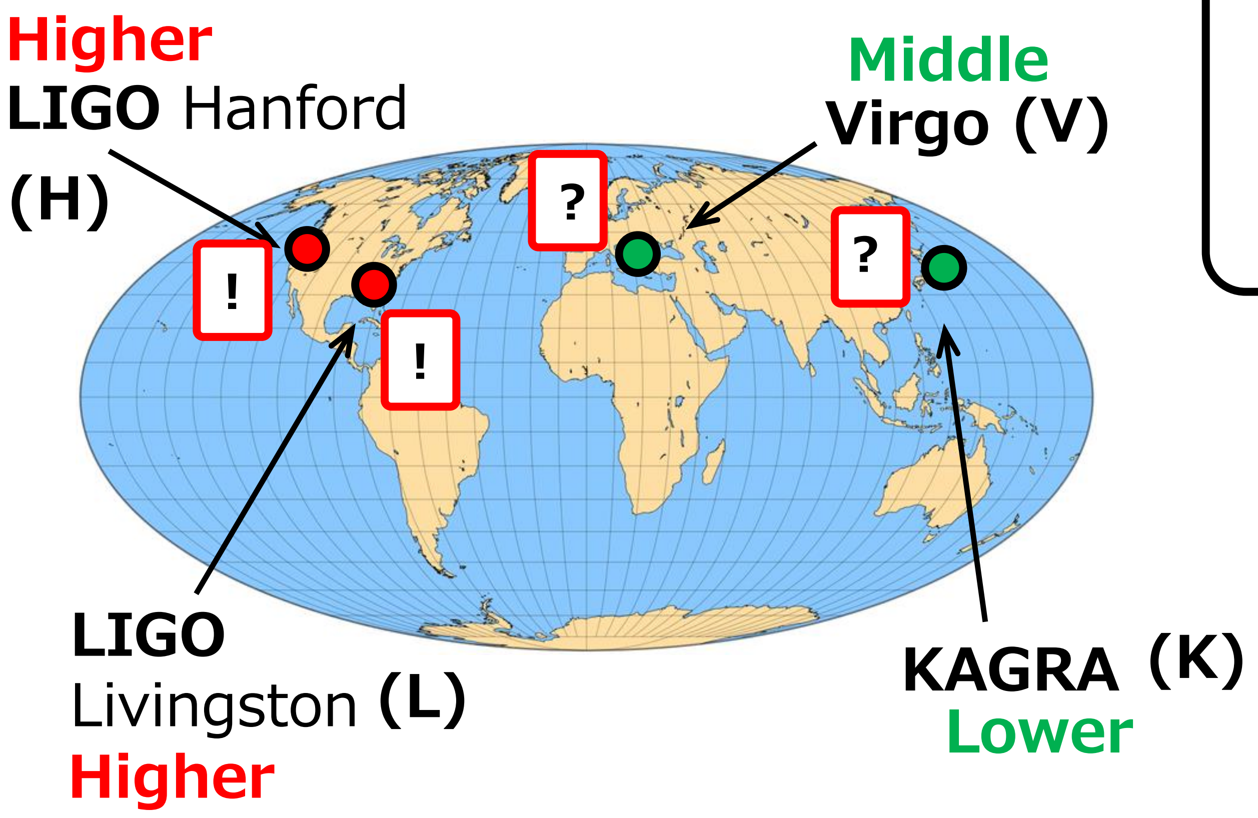


By HLV



[ref] https://gracedb.ligo.org/superevents/public/O3/

In heterogeneous network:



(At the beginning)

Ex.) SNR > SNRth → detection:

→ Not good
for EM-follow up

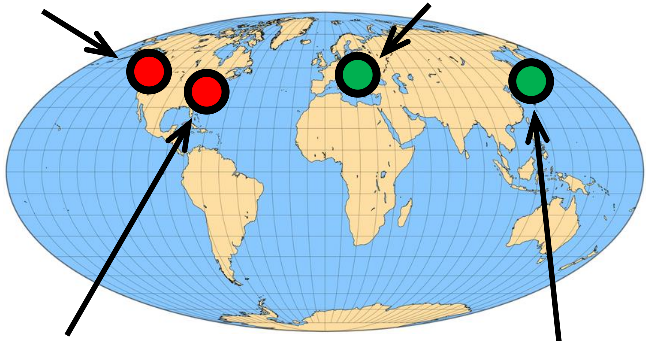
Target:

*** Set a lower threshold,**
&
*** Avoid not too many background triggers.**

Hierarchical approach

Higher sensitivity
LIGO Hanford **(H)**

Middle sensitivity
Virgo (V)



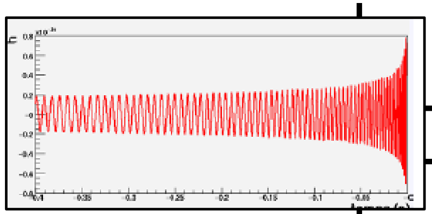
Higher sensitivity
LIGO Livingston **(L)**

Lower sensitivity
KAGRA (K)

(At the beginning)

Sub network by higher sensitive detectors find candidate event.

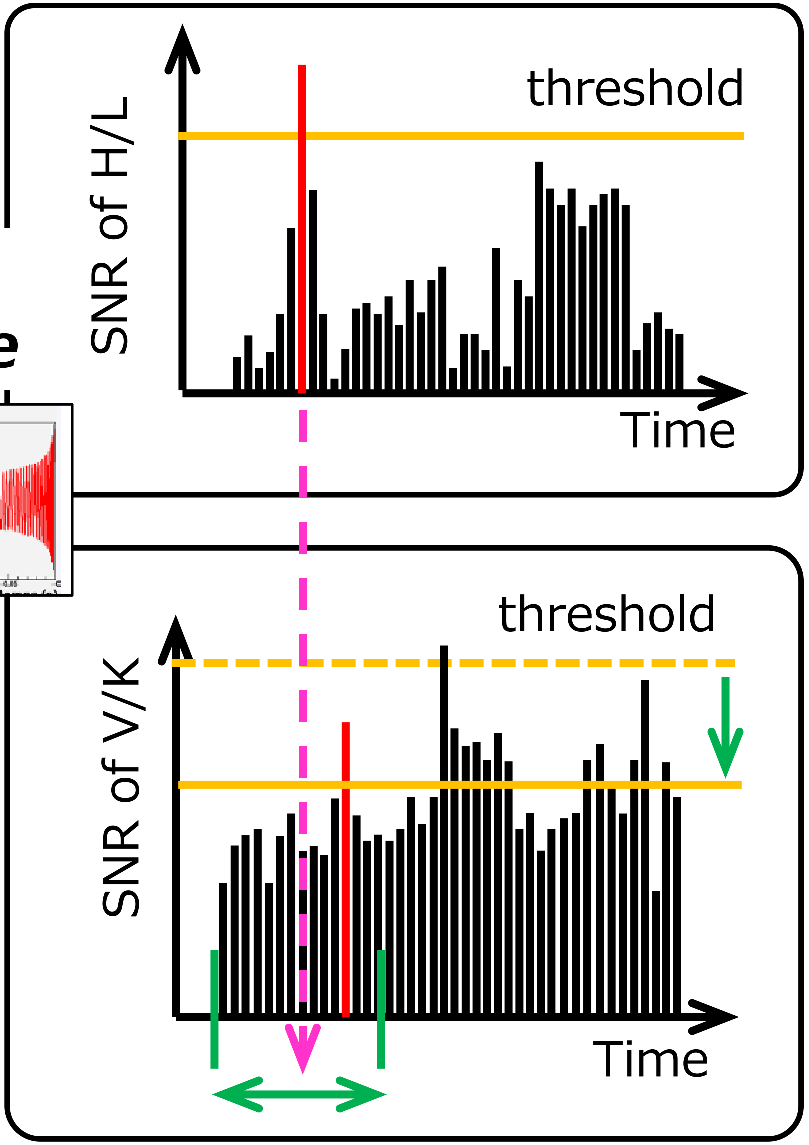
One template



Less sensitive detectors are added into network with

1. lower SNR threshold,
2. same template,
3. a small window around time of double coincidences.

Higher sensitive detector



Lower sensitive detector

Hierarchical approach in fast localization

With LIGO-Virgo / LIGO-KAGRA / LIGO-Virgo-KAGRA network:

→ **Expected performance?**

→ **Required detector sensitivity?**

→ **Optimal SNR threshold?**

Hierarchical approach in fast localization

With LIGO-Virgo / LIGO-KAGRA / LIGO-Virgo-KAGRA network:

Unique **Hierarchical search with heterogeneous network**

Performance by LIGO-Virgo network
→ Published at *Astroparticle Physics*, **Y. Fujii** et. al. (2019)

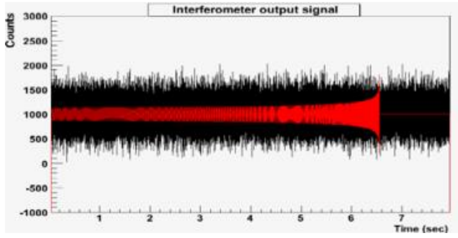
Calculation set up:

1. GW-EM pipeline (for GWs from BNS)

Matched filtering — Sky map

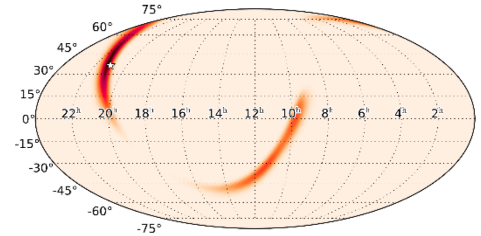
GW detector → MBTA → BAYESTAR → EM telescopes

Signal



Event info:
SNR,
arrival time,
etc.

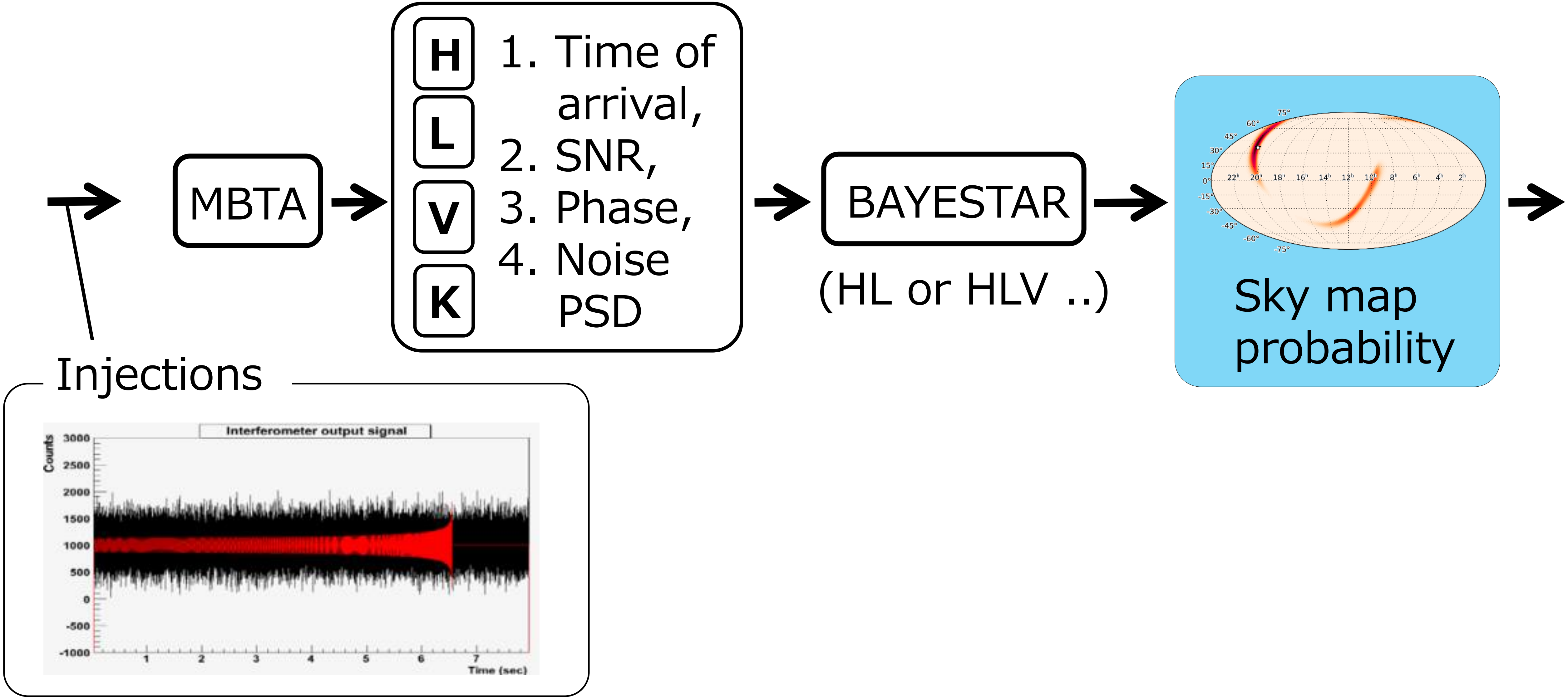
Sky map probability



2. Two LIGOs (54 Mpc-BNS range), Virgo, KAGRA (< 54 Mpc)

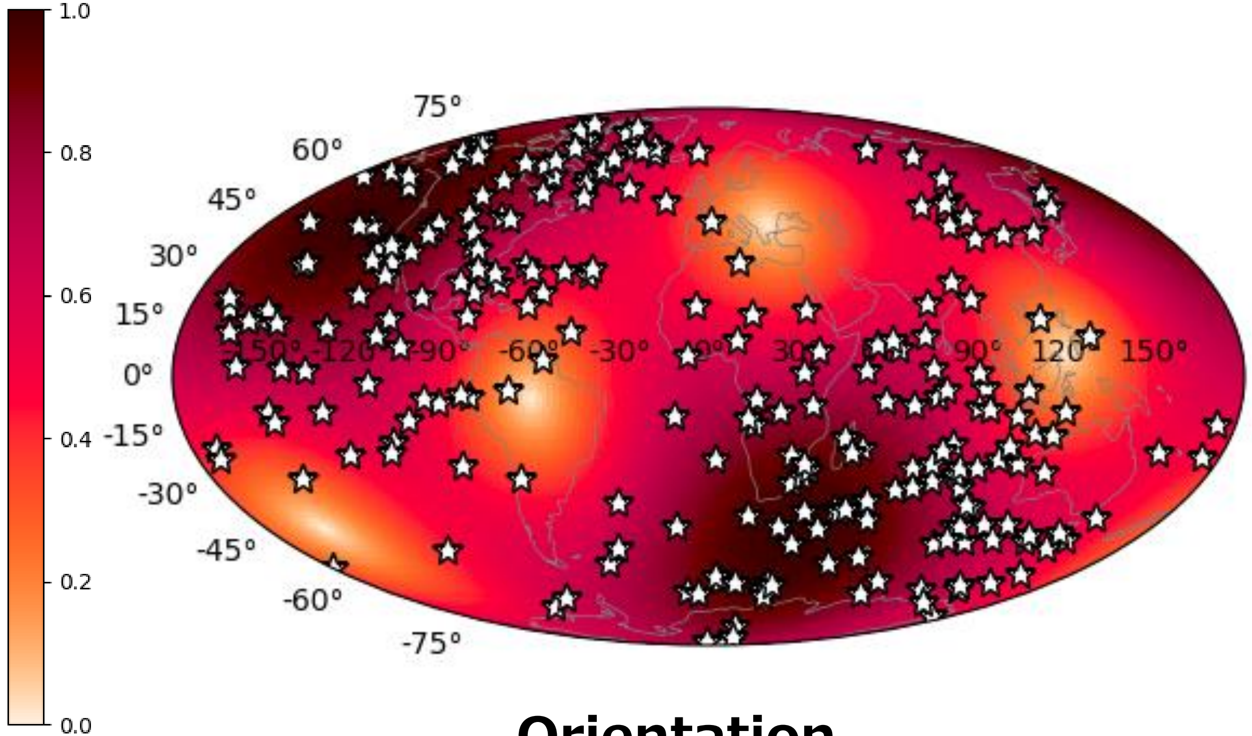
→ Relative sensitivities is important.

Main flow:

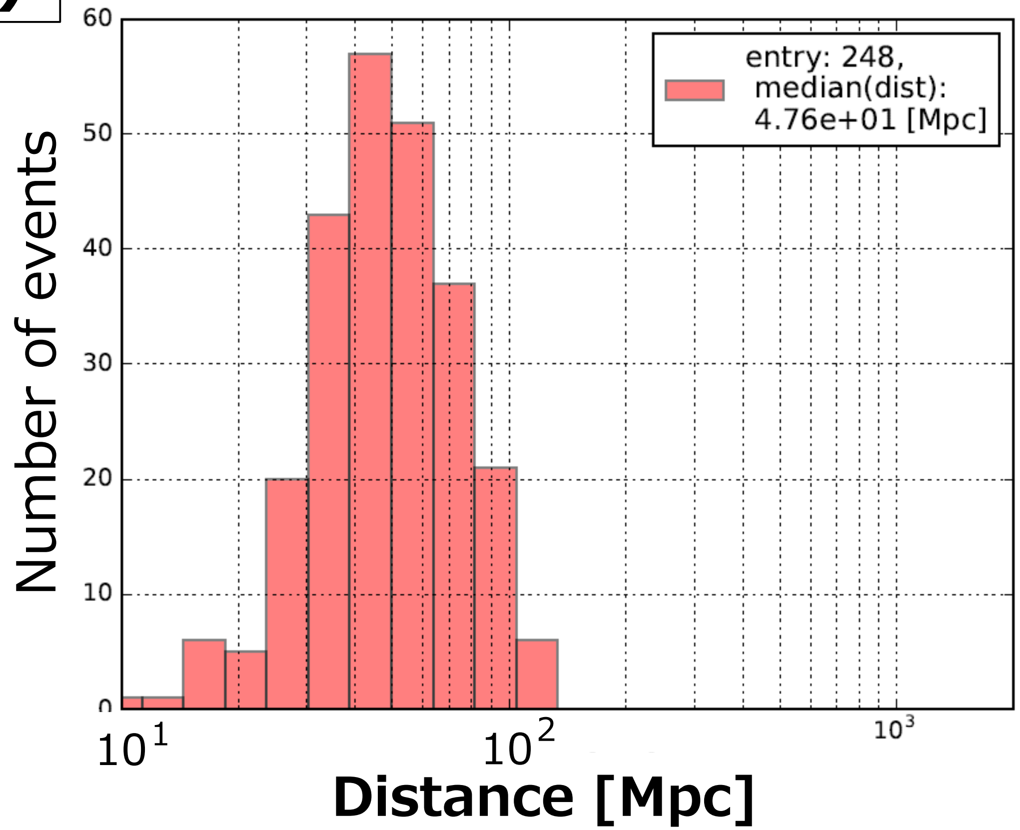

MBTA
H
L
V
K
1. Time of arrival,
2. SNR,
3. Phase,
4. Noise PSD
BAYESTAR
(HL or HLV ..)
Sky map probability
Injections
Interferometer output signal
Counts
Time (sec)

Main flow:

Injections (number of events: 248)



Orientation
(with LIGO antenna pattern)



detected by LIGO network in [1], and randomly selected.
[1] LIGO-P1300187

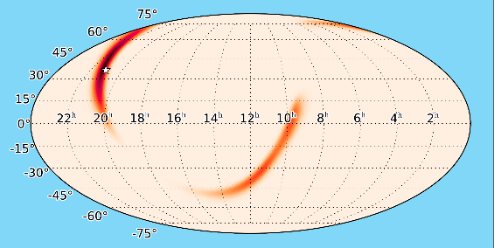
Main flow:

MBTA → H L V K

1. Time of arrival,
2. SNR,
3. Phase,
4. Noise PSD

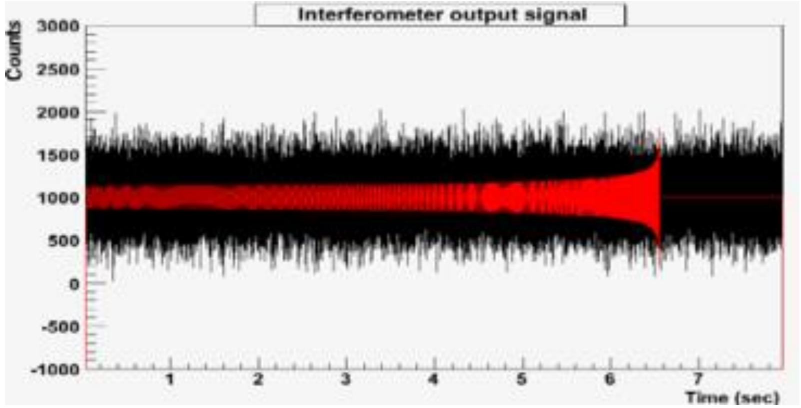
→ BAYESTAR →

(HL or HLV ..)



Sky map probability

248 Injections



Main flow:

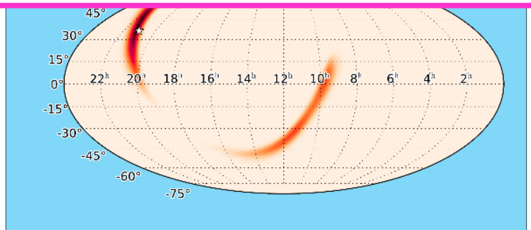
248 Injections → MBTA →

H **L** **Matched-filtered data**

V **K** **Artificial data**

Time of arrival,
SNR,
Phase,
Noise PSD.

→ BAYESTAR (HL or HLV ..) →



Sky map probability →

Omit matched filtering for V/K:

in order to reduce computational cost.

Instead, generate coincident trigger

from here

Generating **coincident** **triggers**, doubles, triples, ..

→ In the real life,
Not all triggers are related to real GW signals.
Sometimes triggers are from noise

In order to realize this,
As an example, in LIGO-Virgo network case:

(SNR > SNR_{th}) and (no noise trigger) → $HLV_{injection}$

(SNR < SNR_{th}) and (no noise trigger) → HL

(noise trigger) → HLV_{noise}

Main flow:

248 Injections → MBTA →

H / L: **Matched-filtered data**

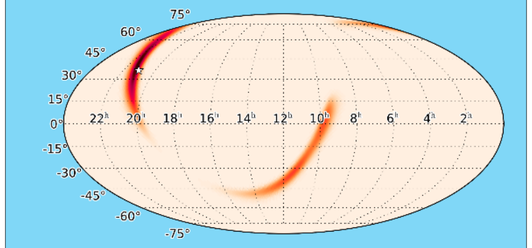
V / K: **Artificial data**

Time of arrival,
SNR,
Phase,
Noise PSD.

from here

→ BAYESTAR →

HL or
HLV$_{noise}$ or
HLV$_{injection}$ ..



Sky map probability →

Attribute the parameters to V$_{noise}$, V$_{injection}$ and ..

Making artificial V/K triggers

(dist. = distribution)

Noise trigger:

$$\begin{bmatrix} \text{SNR} \\ \text{Time} \\ \text{phase} \end{bmatrix} = \begin{bmatrix} \text{Random number from a measured dist.} \\ \text{Time}\_{\text{LIGO}} + \text{Random number from } \textbf{uniform} \text{ dist.} \\ \text{Random number from } \textbf{uniform} \text{ dist.} \end{bmatrix}$$

Injection trigger:

$$\begin{bmatrix} \text{SNR} \\ \text{Time} \\ \text{phase} \end{bmatrix} = \begin{bmatrix} \text{Expected} \end{bmatrix} + \begin{bmatrix} \text{Random number} \\ \text{from } \textbf{Gaussian} \text{ dist.} \end{bmatrix}$$

Main flow:

248 Injections → MBTA →

H **L** **Matched-filtered data**

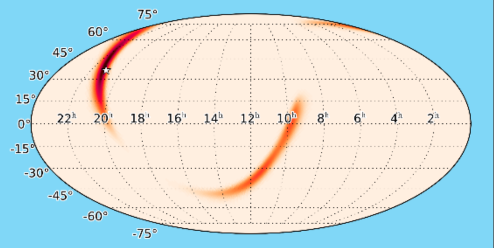
V **K** **Artificial data**

Time of arrival,
SNR,
Phase,
Noise PSD.

from here

→ BAYESTAR →

HL or
HLV$_{noise}$ or
HLV$_{injection}$ ..

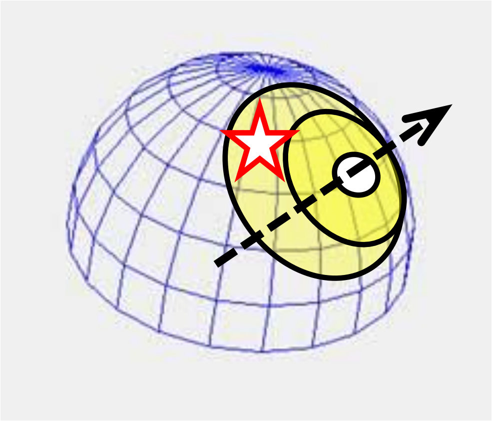


Sky map probability →

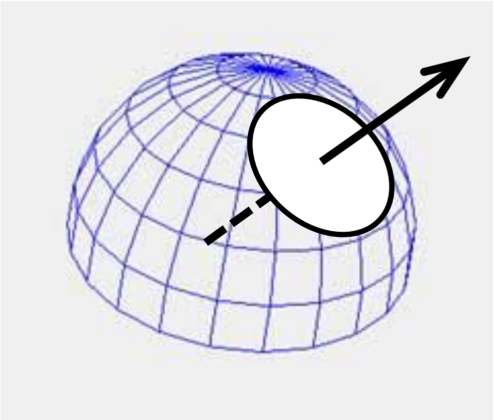
Main flow:

Localization performance

1) **Accuracy**
→ Searched area (deg^2)



2) **Precision**
→ 90 % confidence area (deg^2)

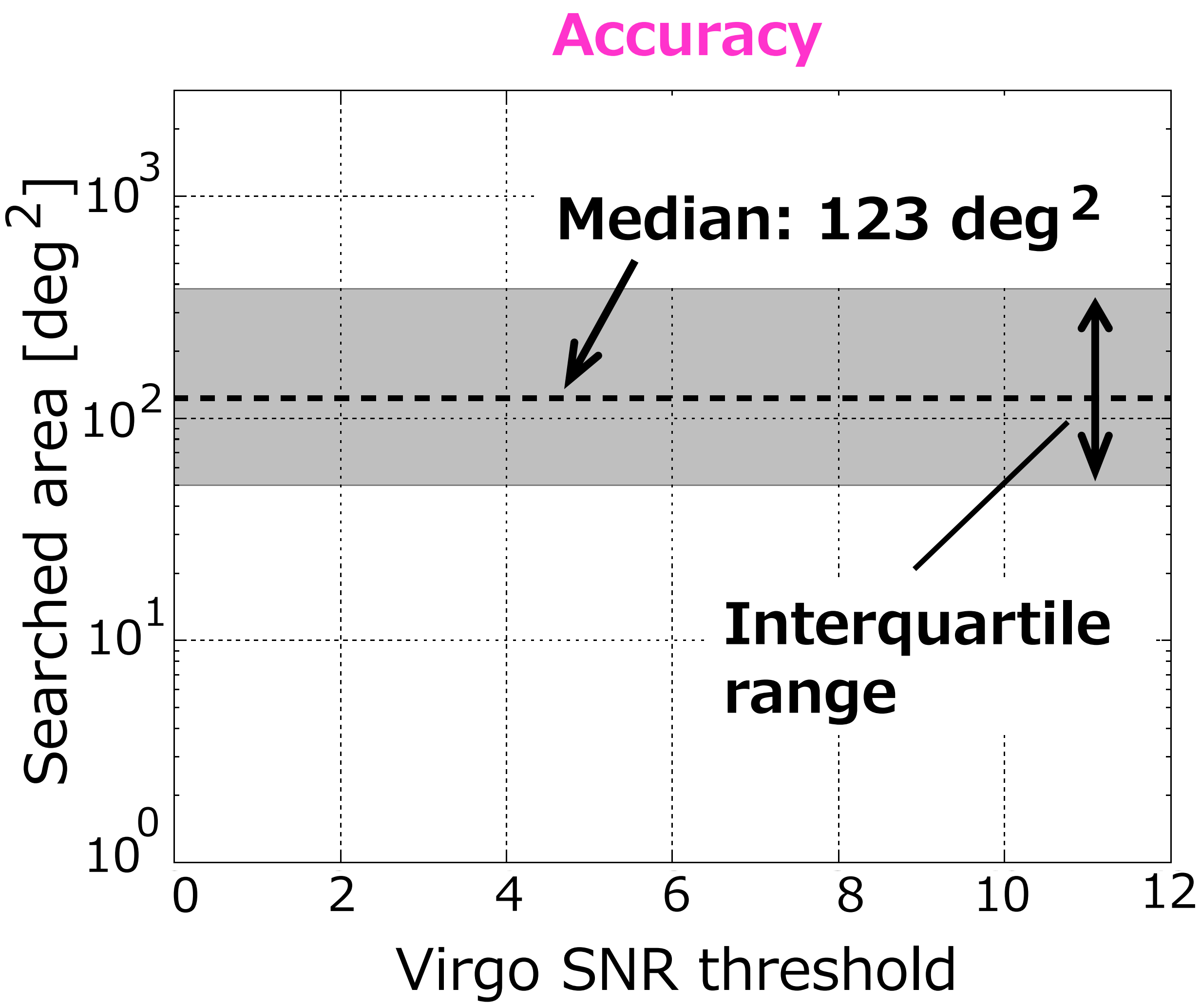


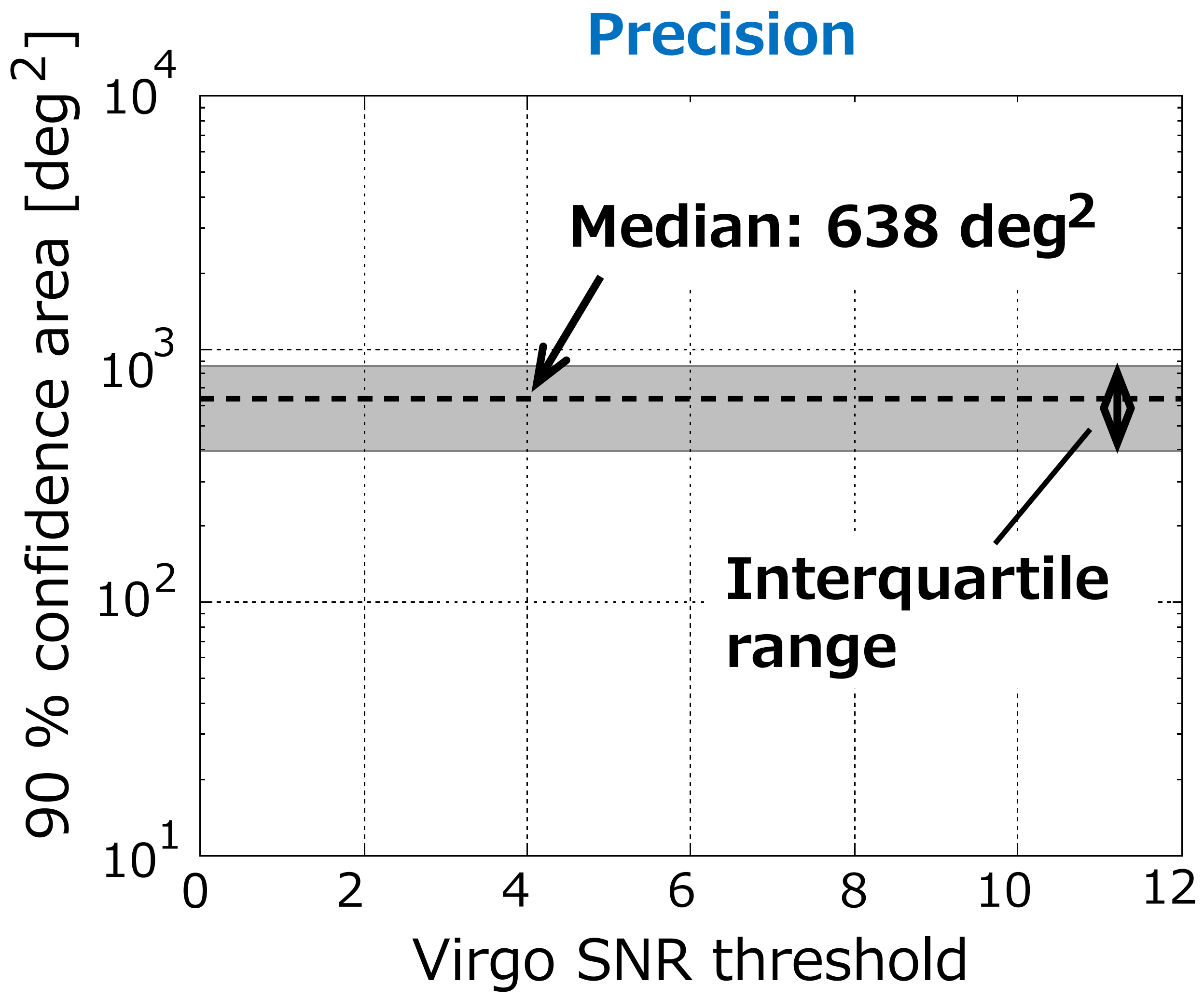
For both, ***smaller*** *is* ***better.***

Median values for 248 events

Performance (HL):

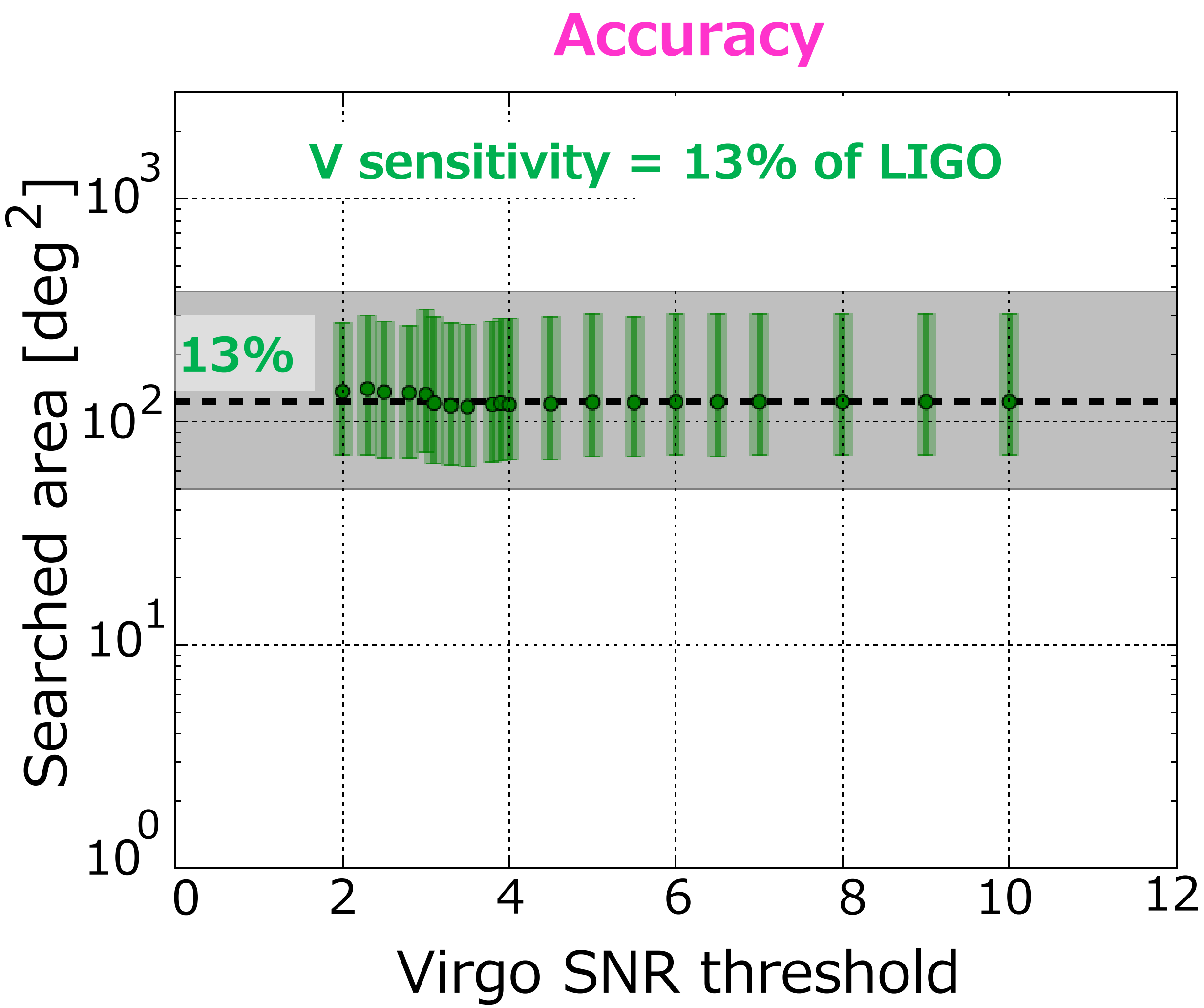
(SNR threshold for H, L = 5., 5.)

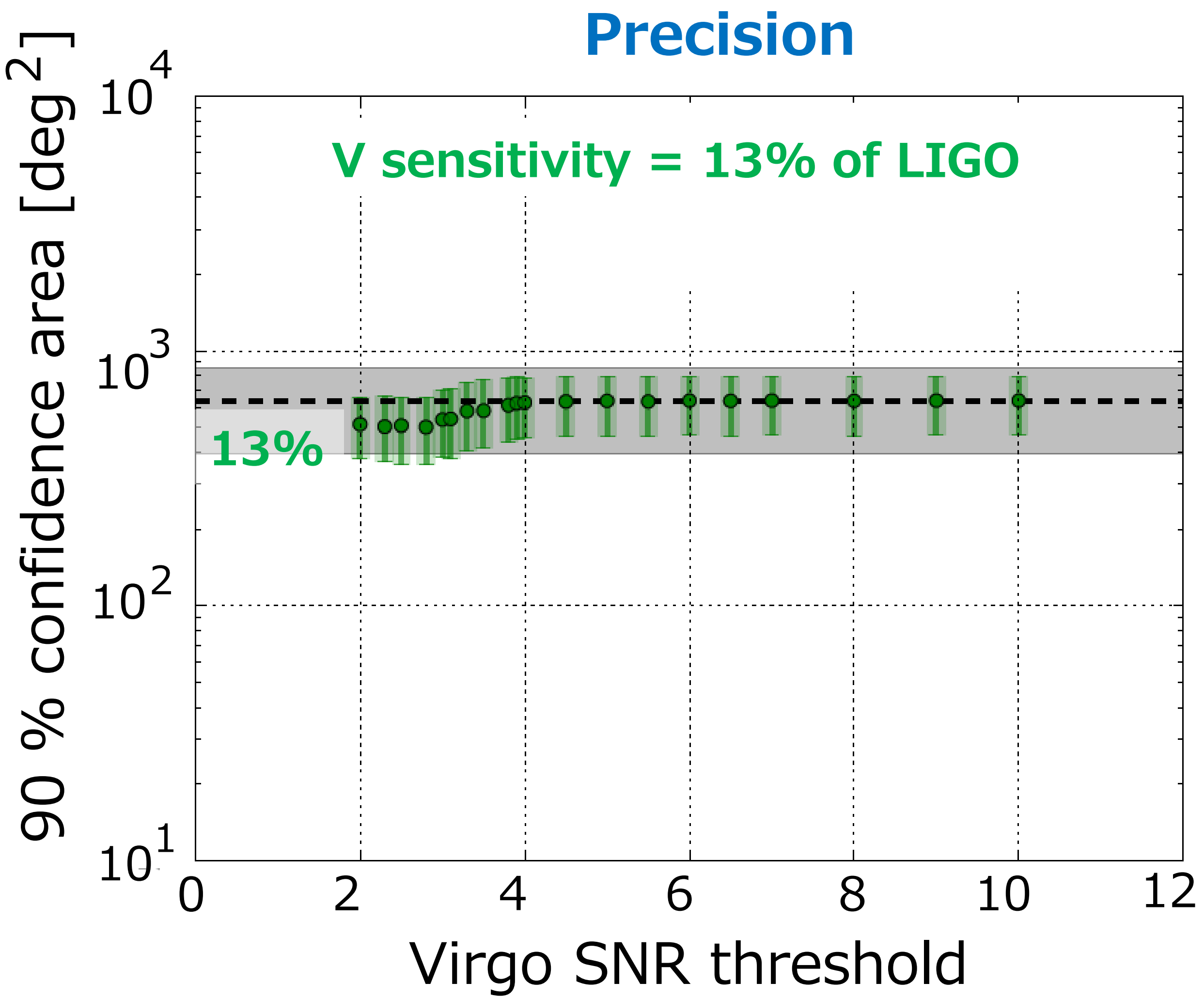




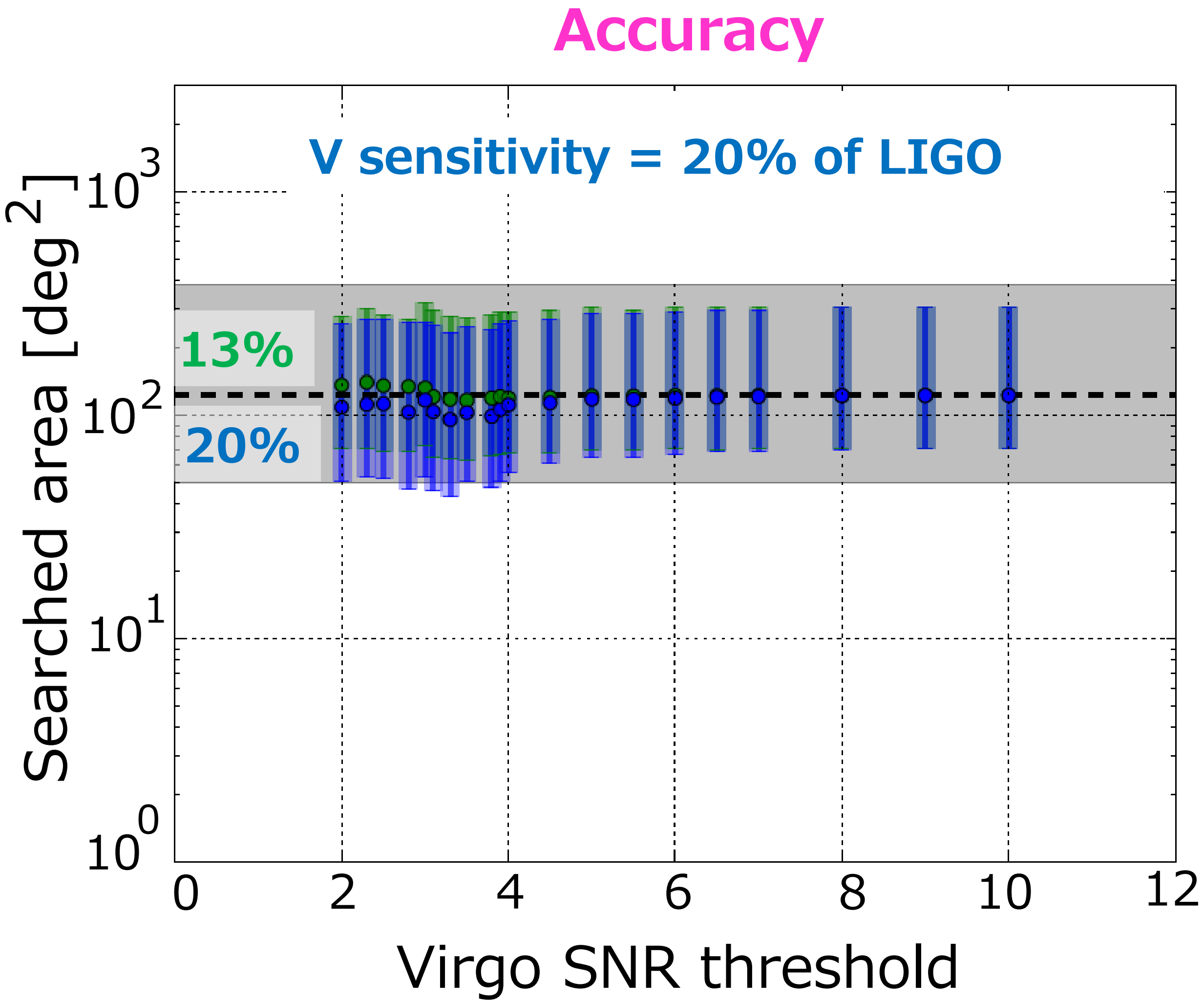
Performance (HLV):

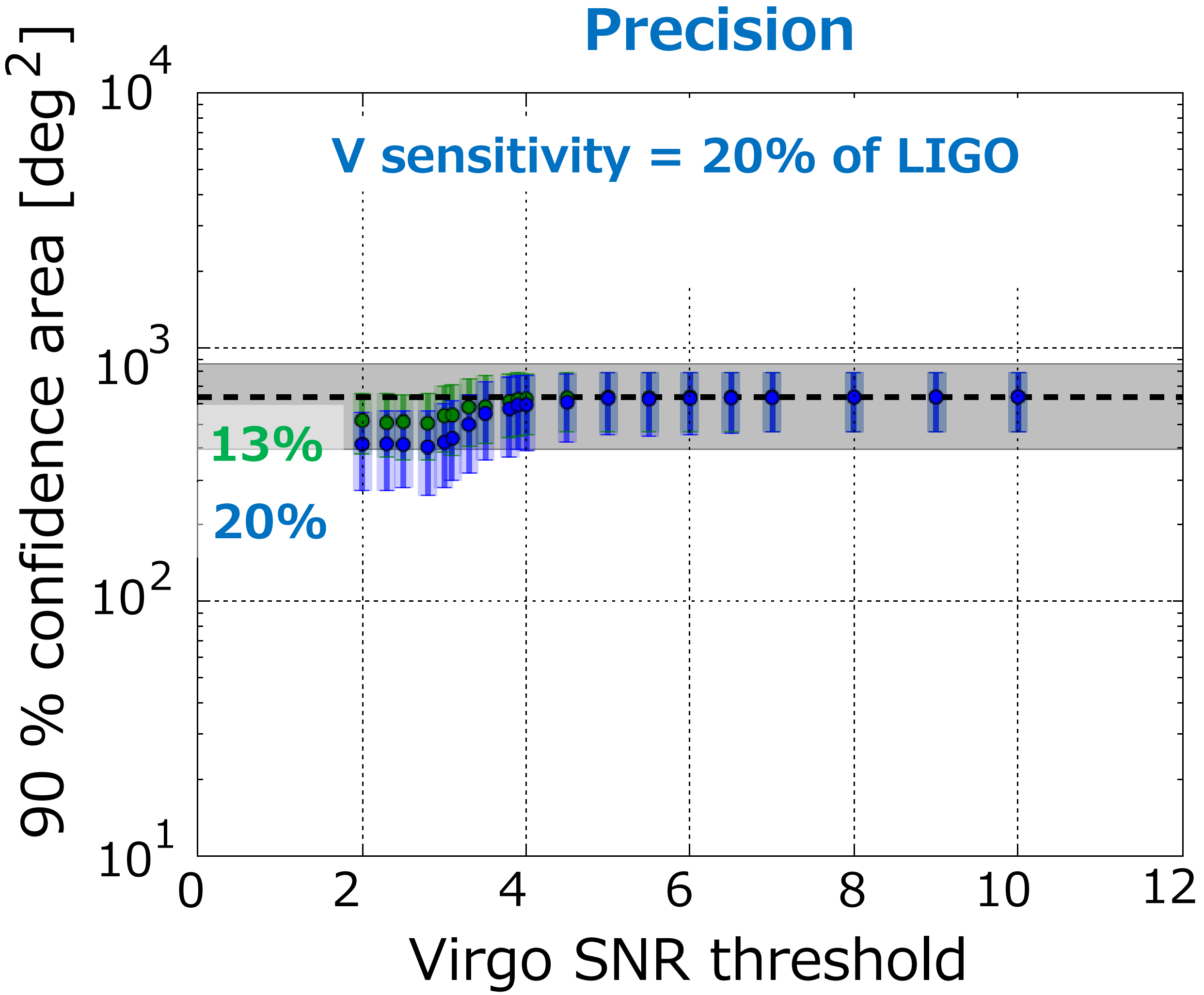
(SNR threshold for H, L = 5., 5.)





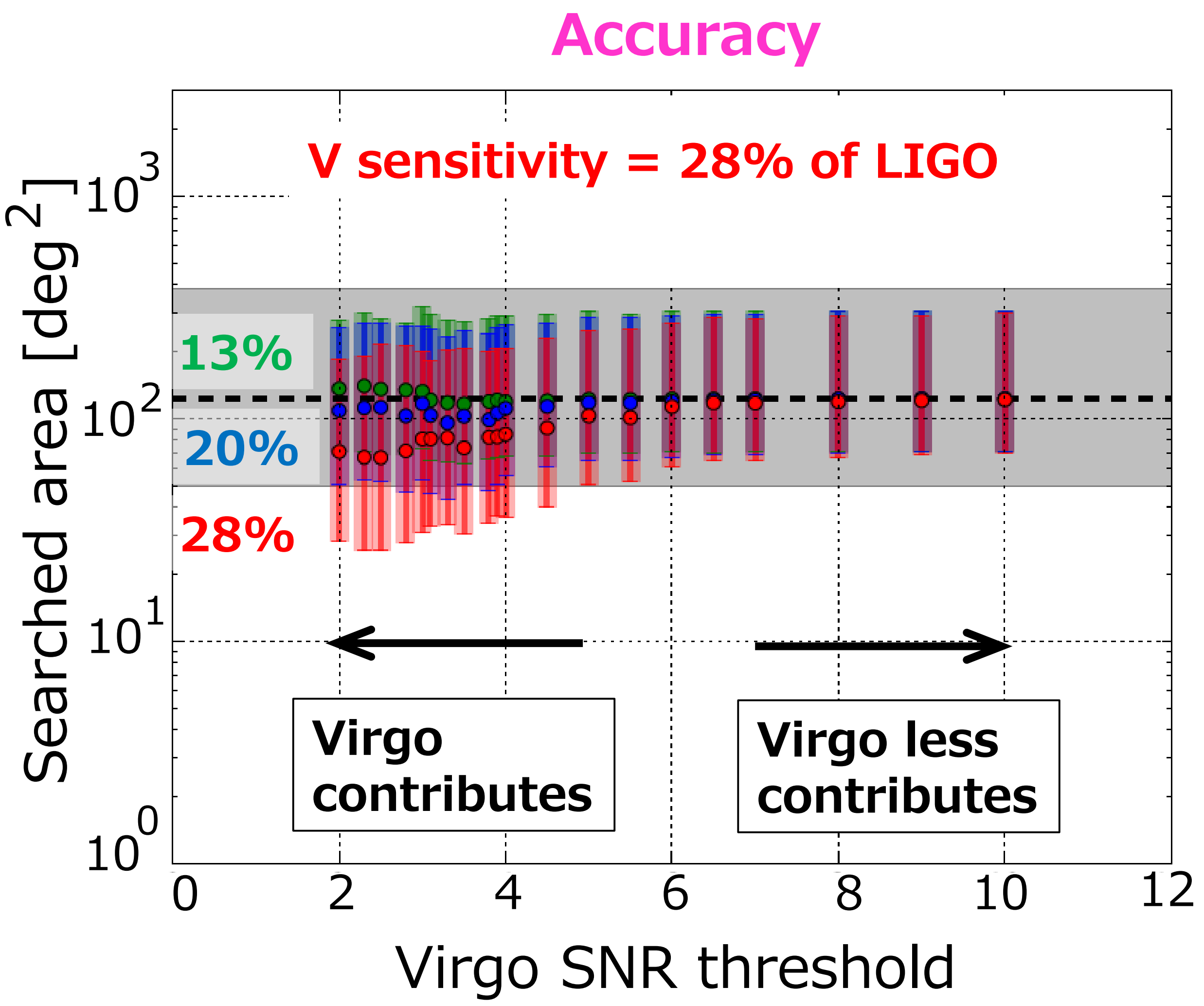
Performance (HLV): (SNR threshold for H, L = 5., 5.)

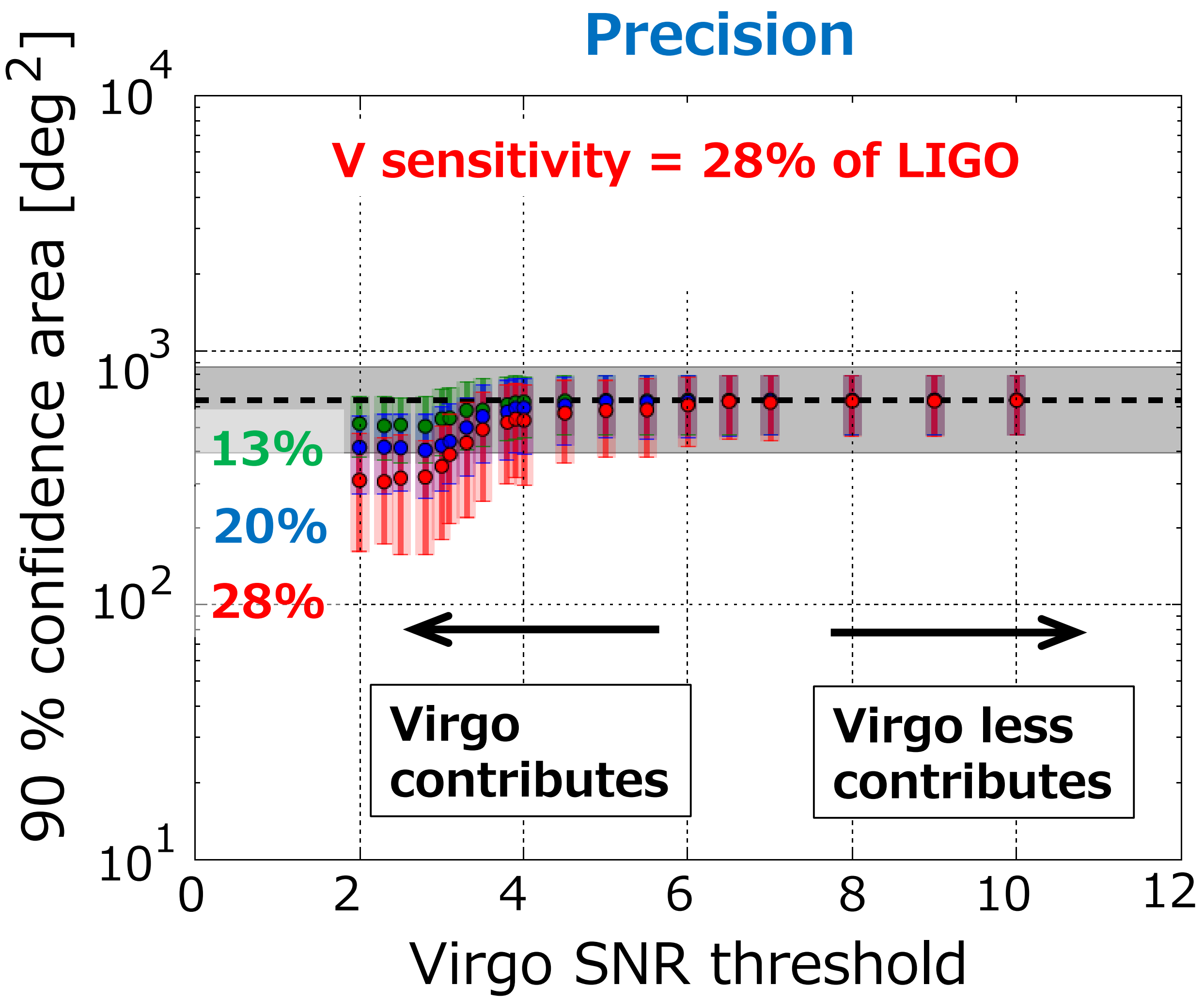




Performance (HLV):

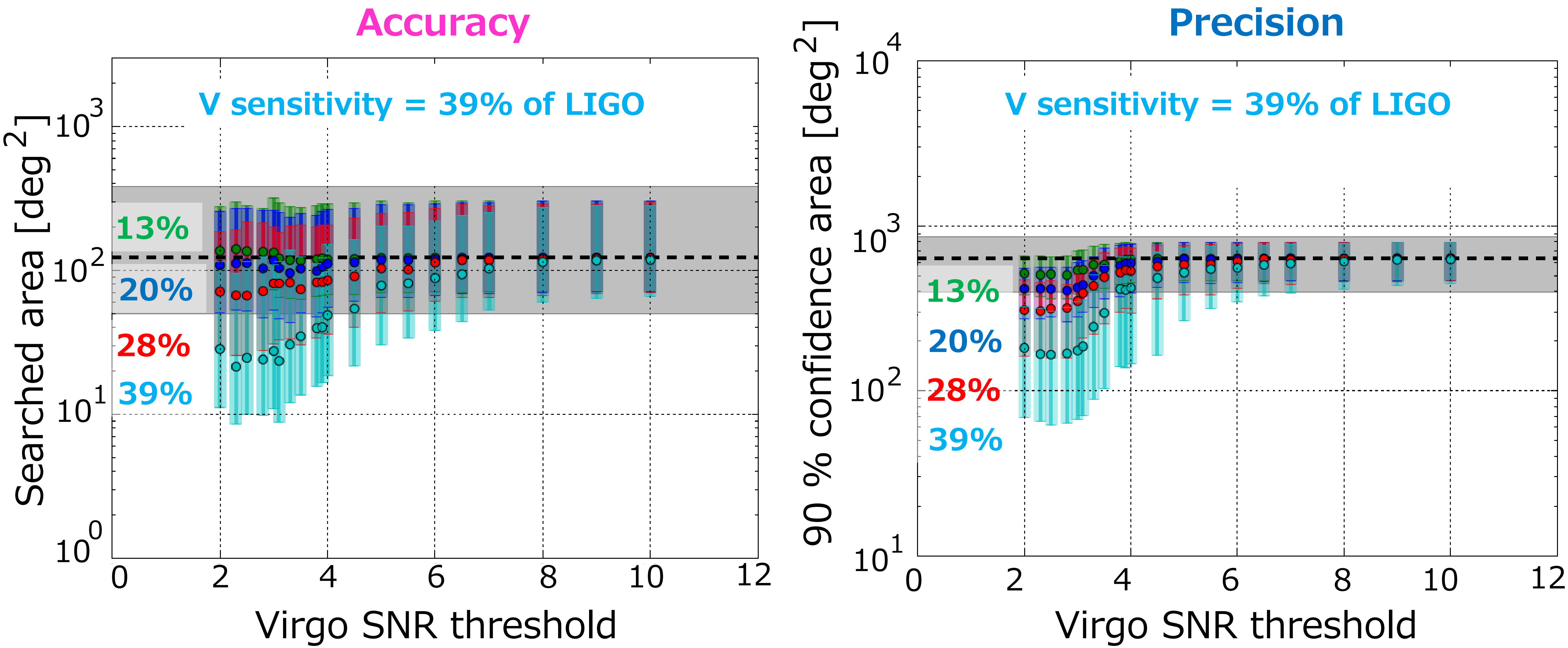
(SNR threshold for H, L = 5., 5.)



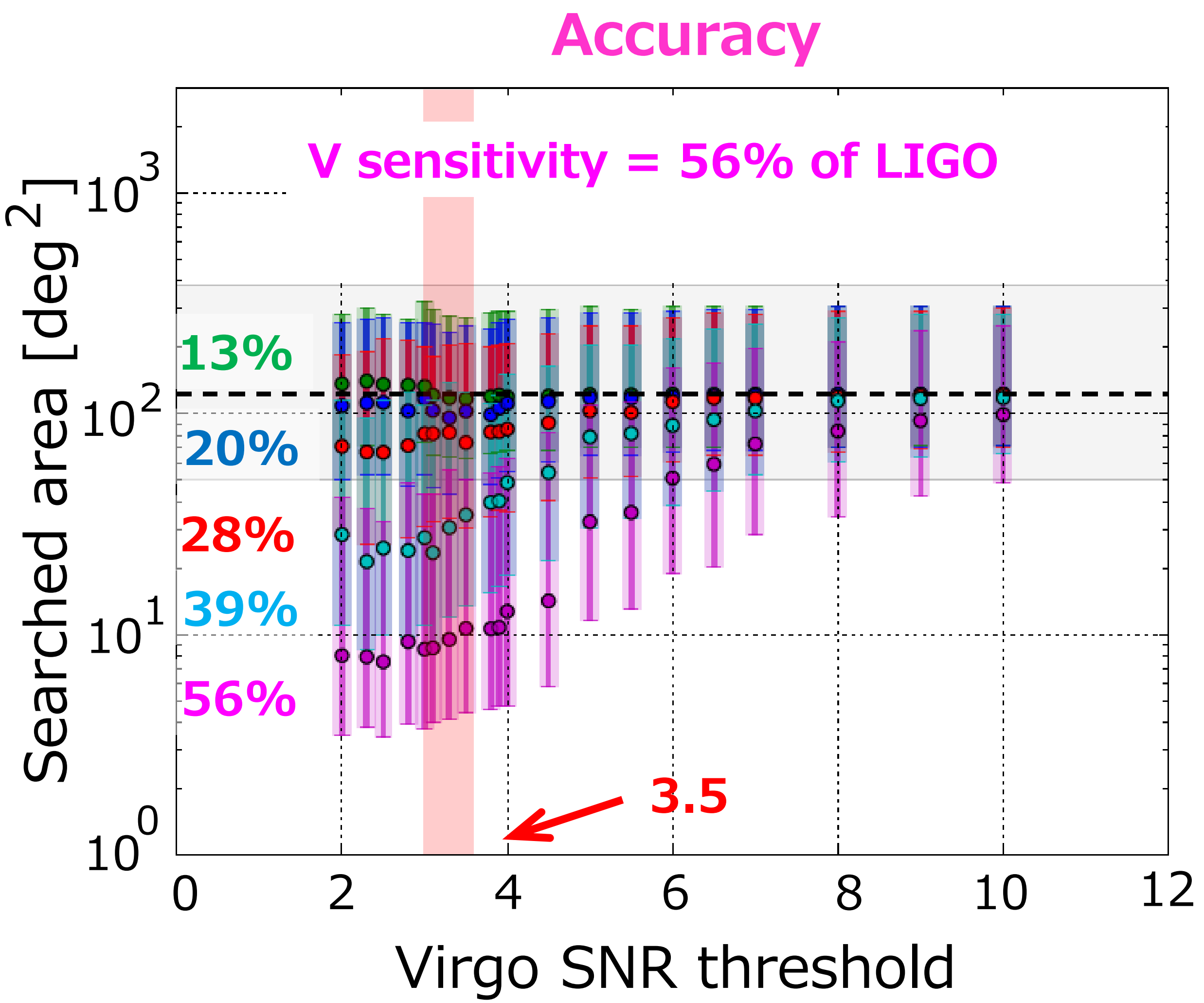


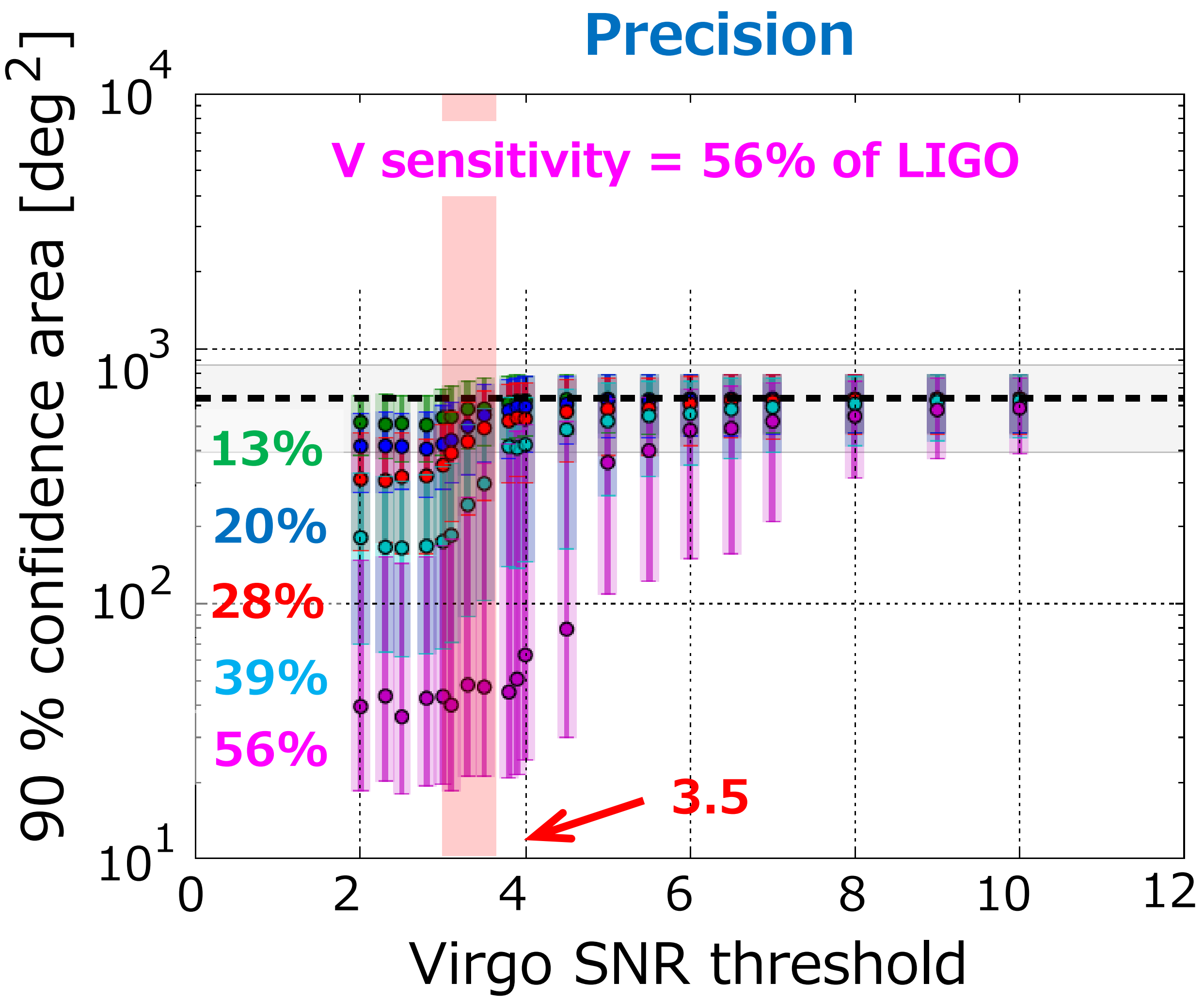
Performance (HLV):

(SNR threshold for H, L = 5., 5.)



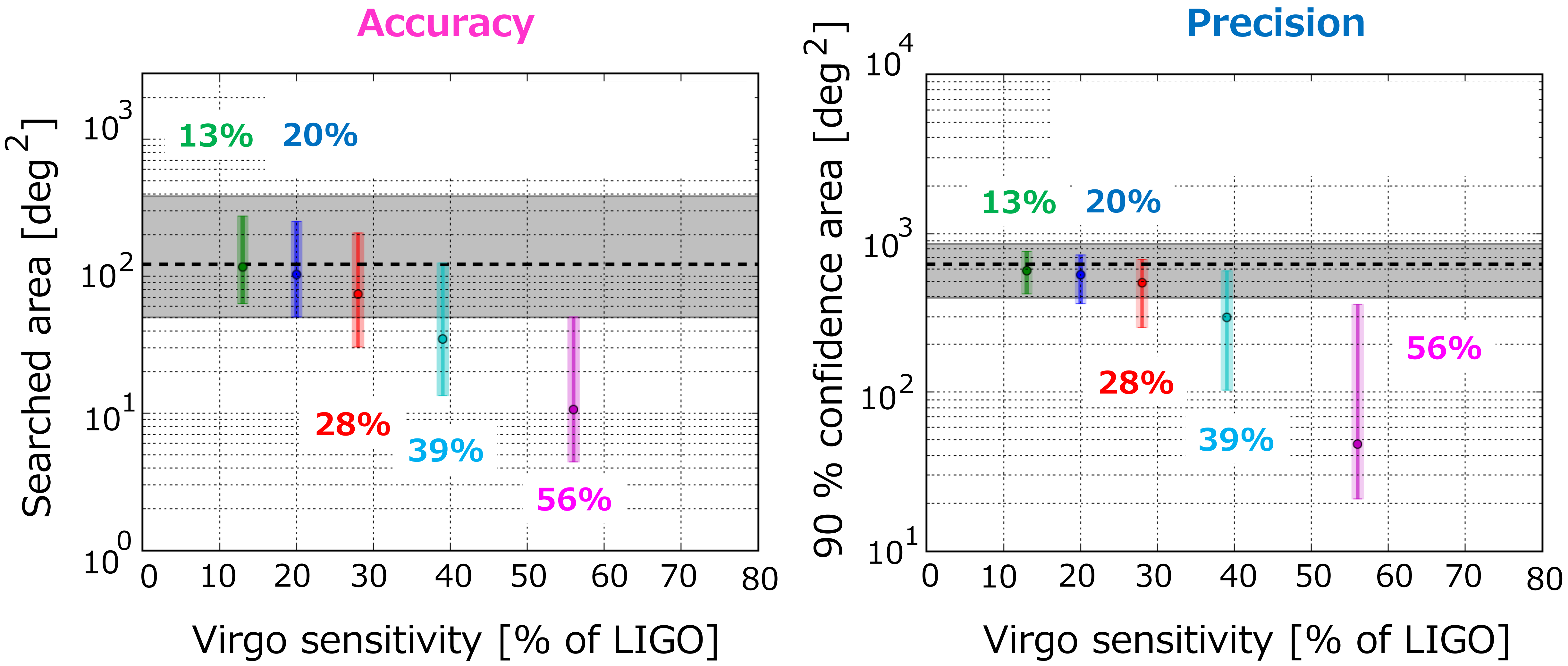
Performance (HLV): (SNR threshold for H, L = 5., 5.)





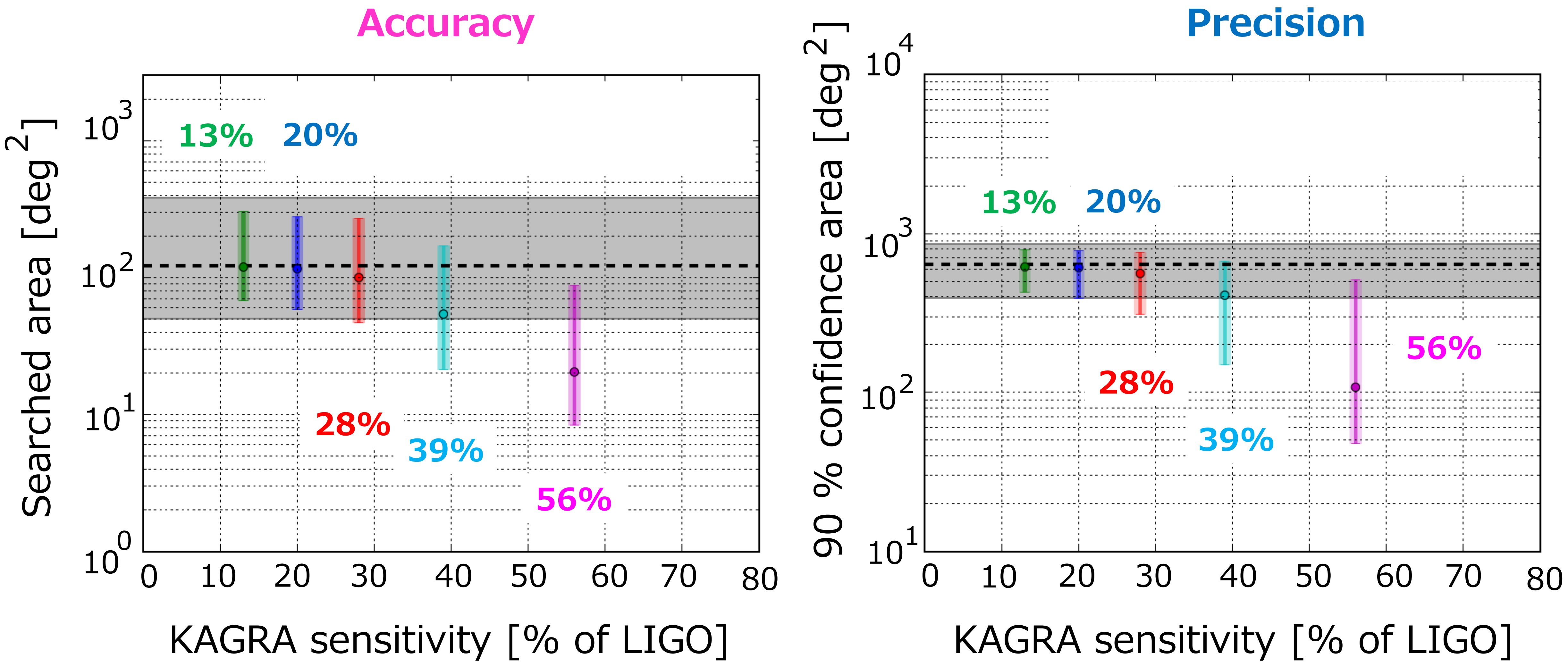
V SNR threshold = 3 ~ 3.5

Performance (HLV): (SNR threshold for H, L, V = 5, 5, 3.5)



Required: Virgo sensitivity > 20% of LIGO

Performance (HLK): (SNR threshold for H, L, K = 5, 5, 3.5)



Required: KAGRA sensitivity > 28% of LIGO

Hierarchical approach by 4-detector network

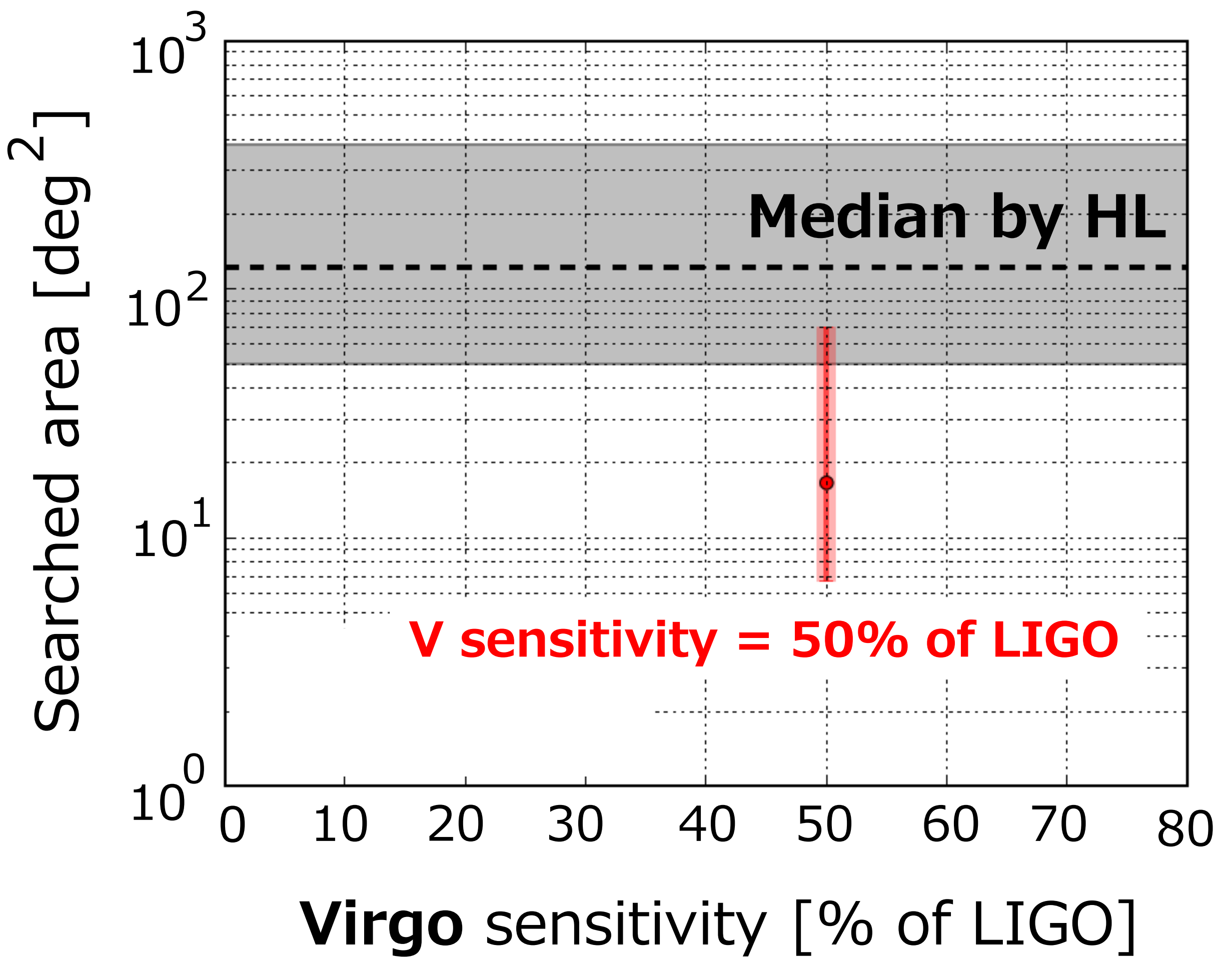
Assuming that:

1. Relative sensitivity
Virgo = 0.5 * LIGO

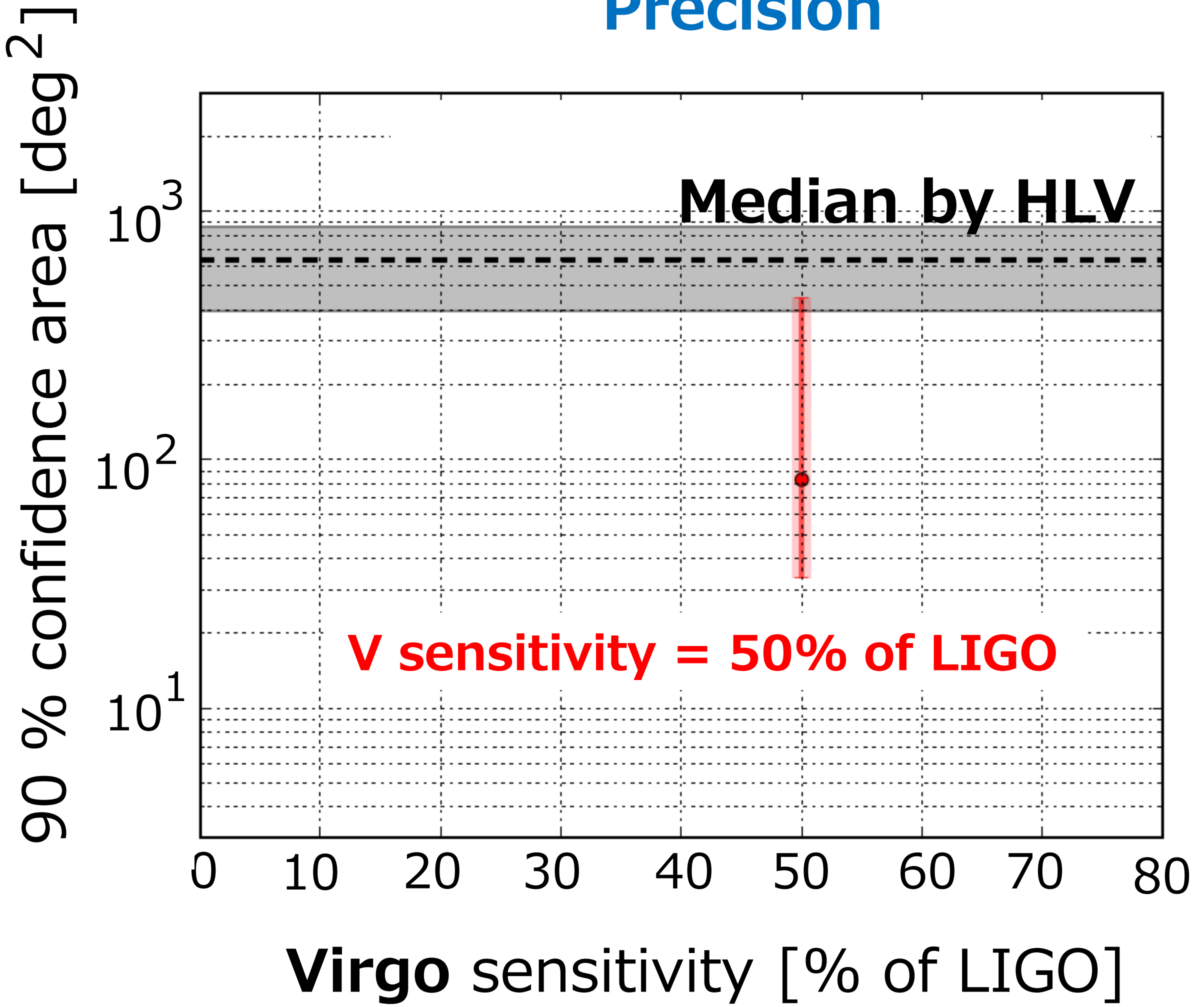
2. SNR threshold
LIGO = 5
Virgo = 3.5

Performance (HLV): (SNR threshold for H, L, V = 5, 5, 3.5)

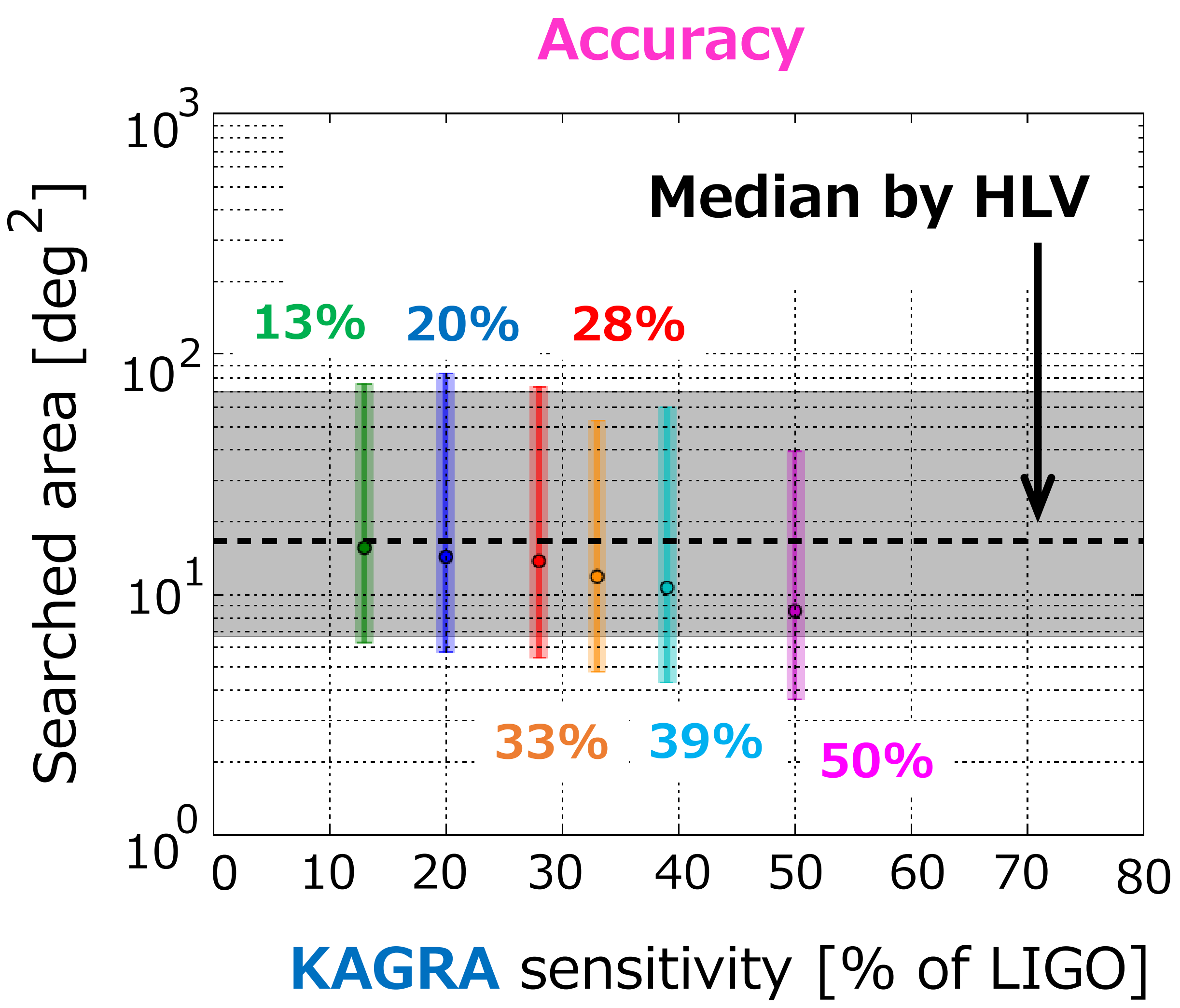
Accuracy

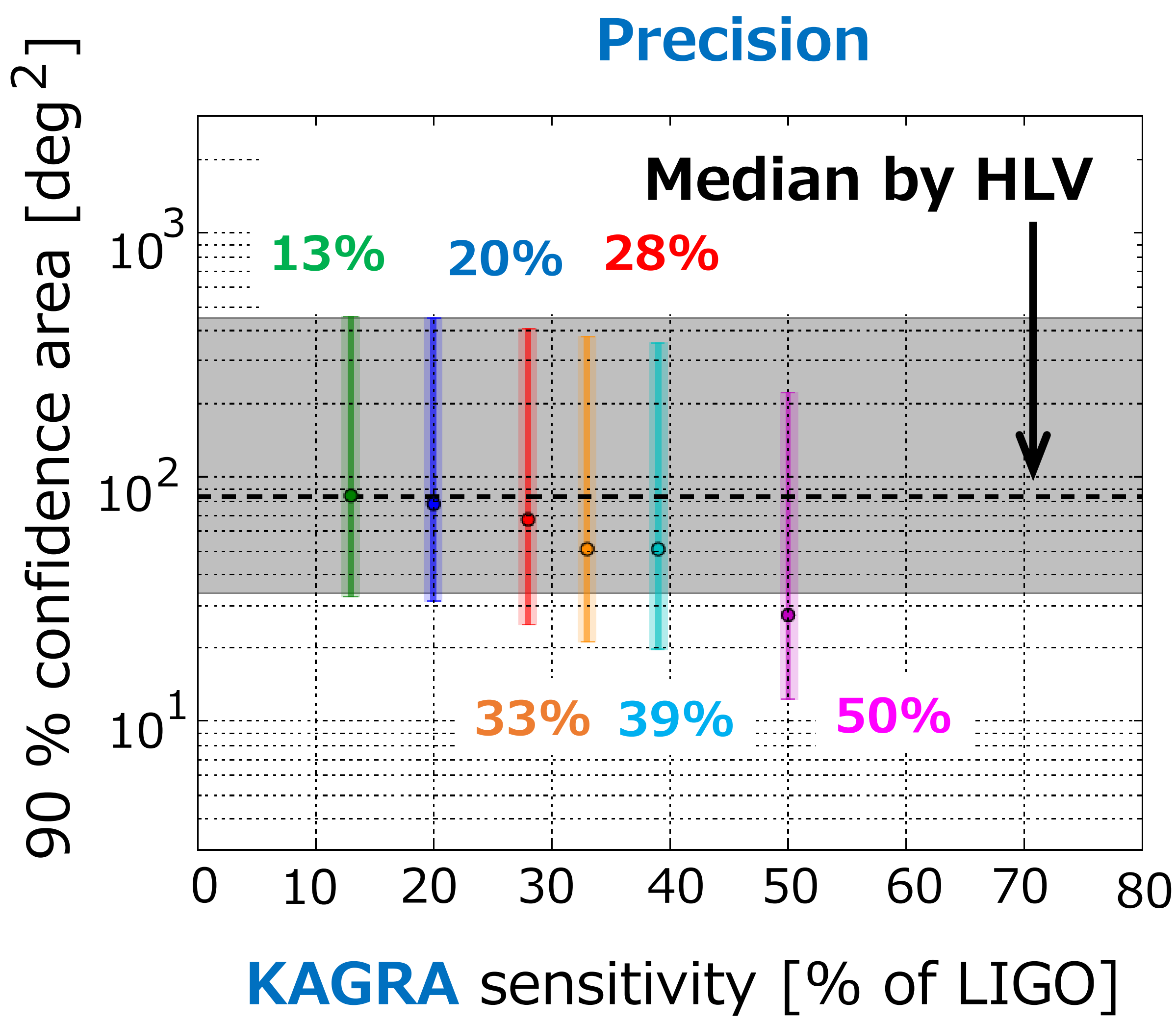


Precision



Performance (HLVK): (SNR threshold for H, L, V, K = 5, 5, 3.5, 3.5)





Required: KAGRA sensitivity > 28% of LIGO

Summary of hierarchical approach

* Required detector sensitivity (at SNR threshold 3.5):

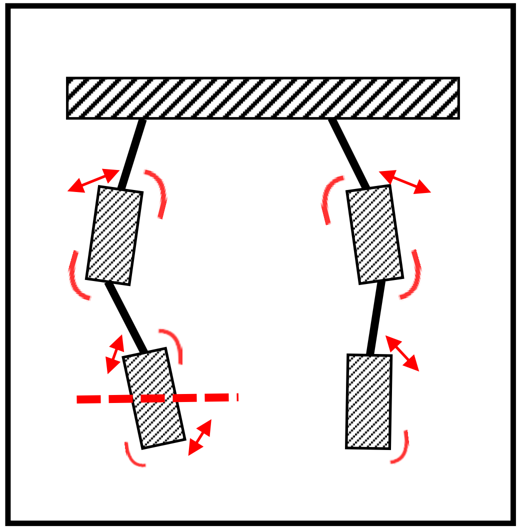
	Relative sensitivity
• **HLV-network:**	Virgo sensitivity > 0.2 * LIGO
• **HLK-network:**	KAGRA sensitivity > 0.28 * LIGO
• **HLVK-network:**	KAGRA sensitivity > 0.28 * LIGO

→ **The hierarchical approach improves the fast localization in the heterogeneous network, using existing low-latency infrastructure.**

Not only fast localization,
but also higher network duty cycle → **key for EM follow up**

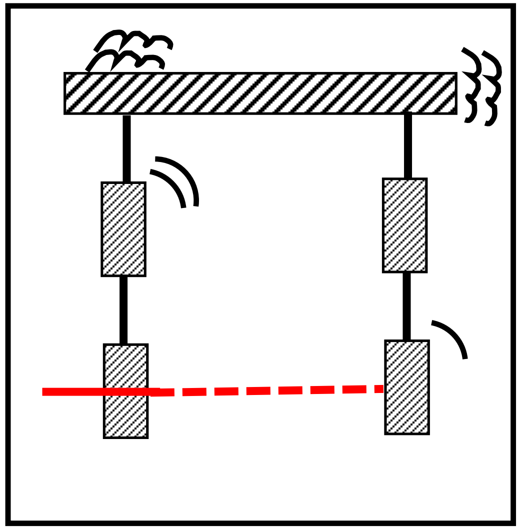
As more practical aspect,
Robust operation of fourth detector

Cannot operate interferometer



→

Demanded for stable operation



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My main research

1. Introduction
2. Benefit of adding detectors to the observation network

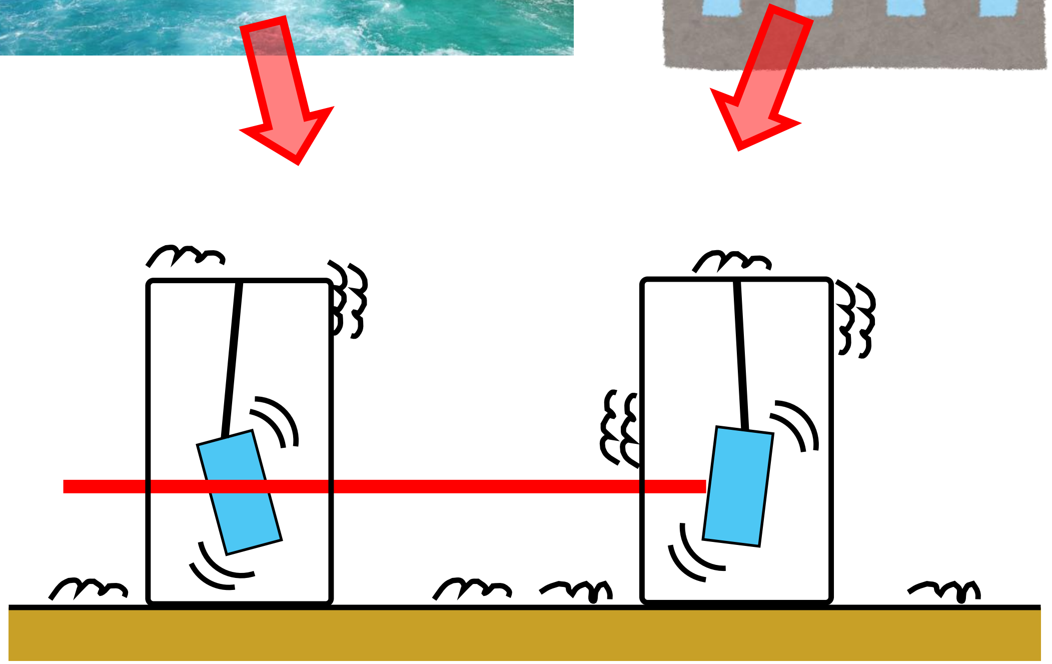
→ 3. Low frequency vibration isolation
4. KAGRA seismic attenuation system

5. Suspension control design
6. Performance test of local control for KAGRA Type-A suspension

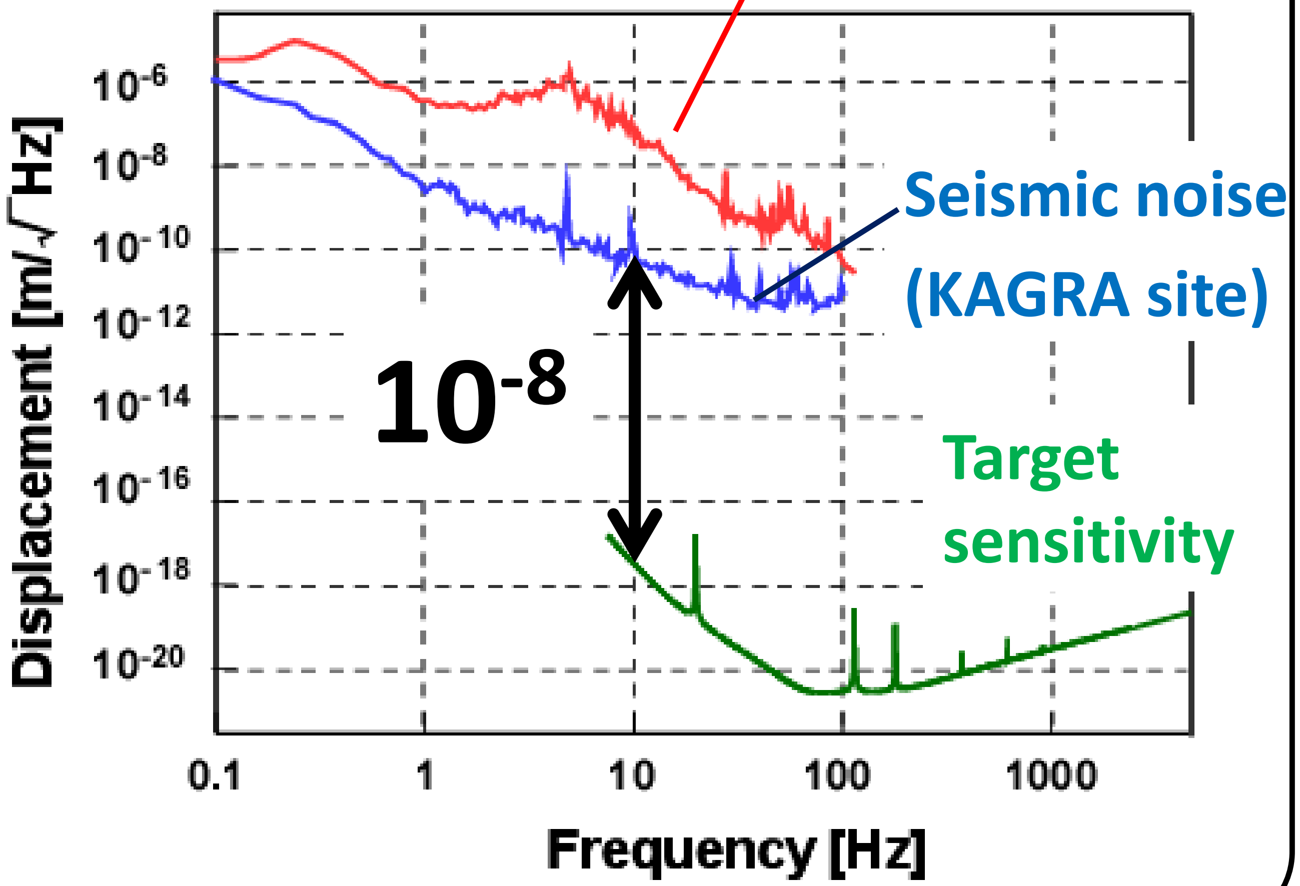
7. Summary

→ Type-A suspension controls toward lock acquisition

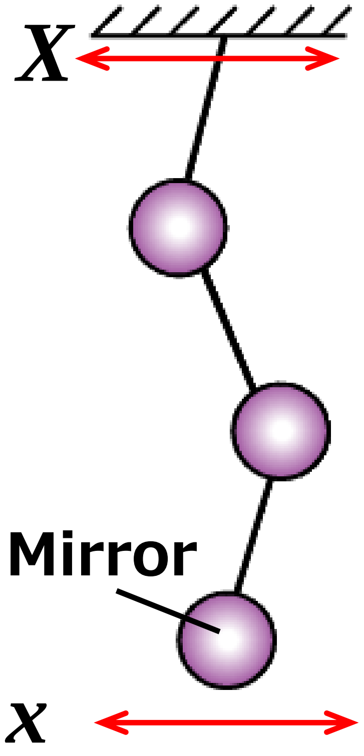
Why pendulum?

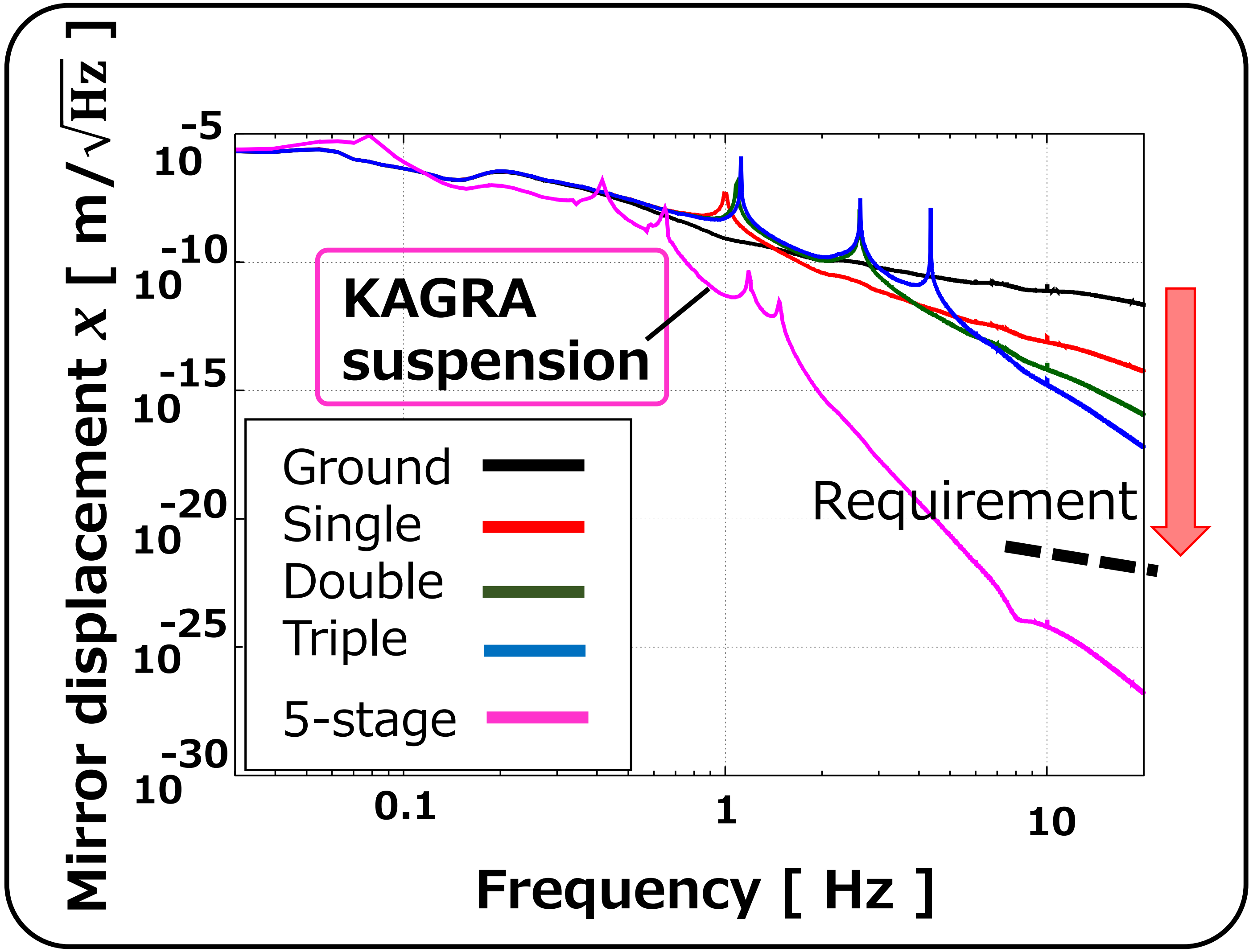


→ To treat seismic noise

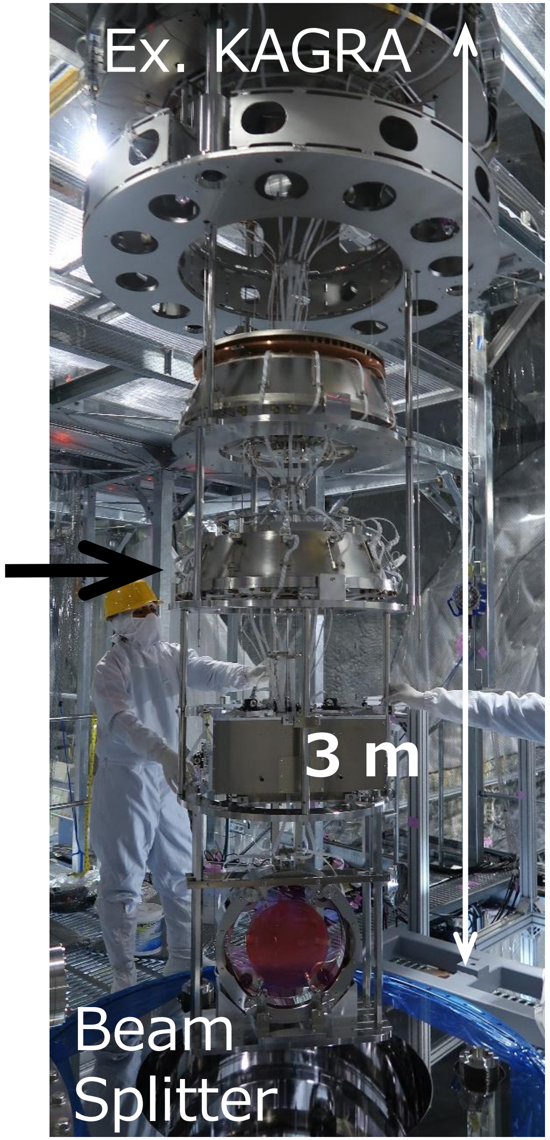


Seismic noise attenuation → pendulum





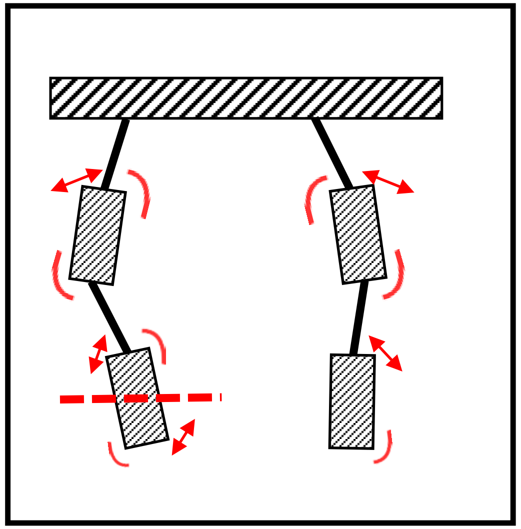
(BS/SRs-suspension case)

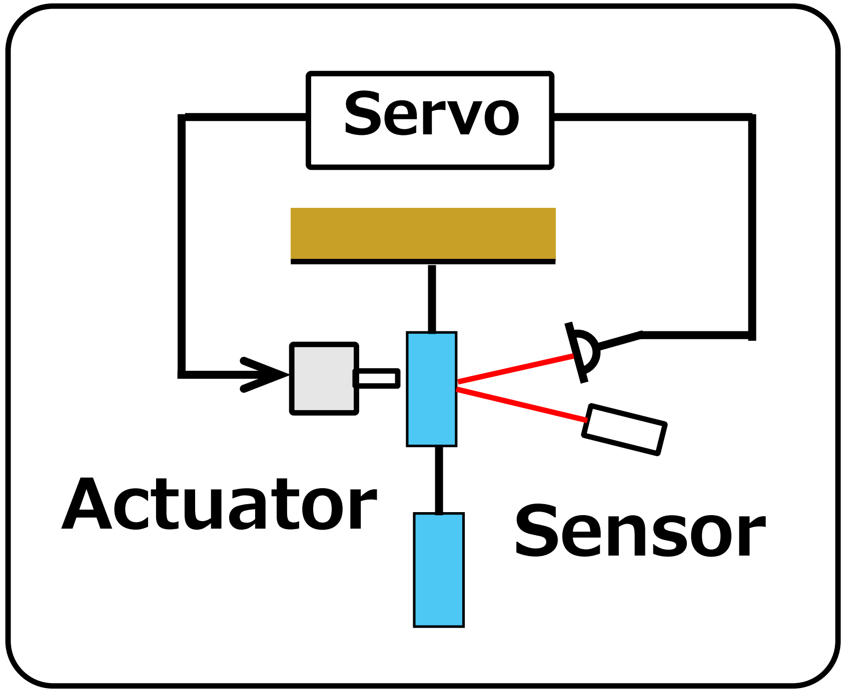


Resonance damping / Mirror Alignment → necessary

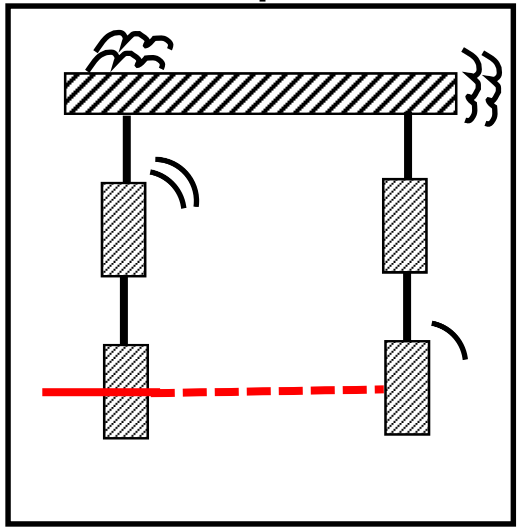
→ Control system

Cannot operate interferometer





Demanded for stable operation



＊ Damp resonances.

＊ Freeze the mirrors

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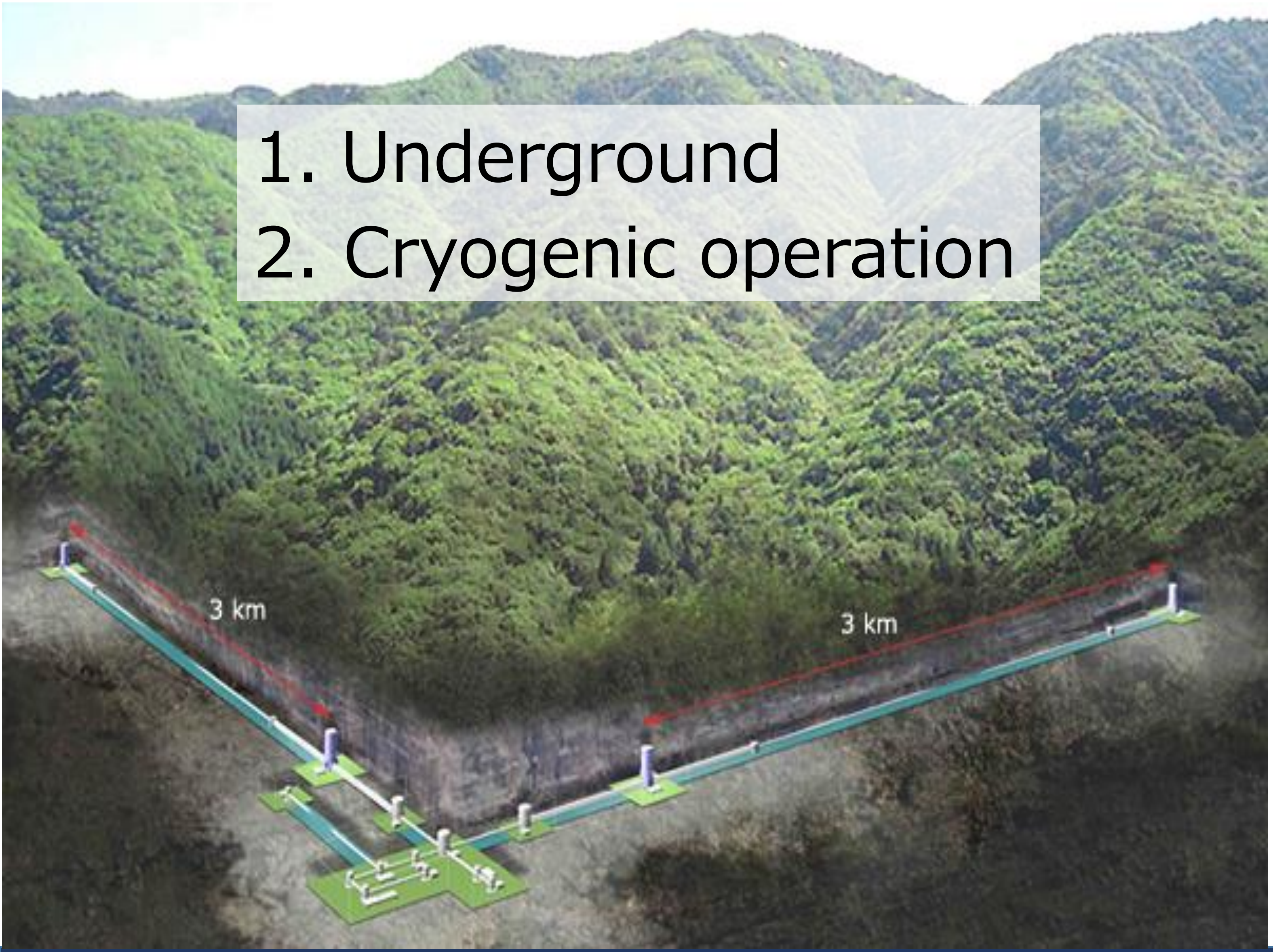
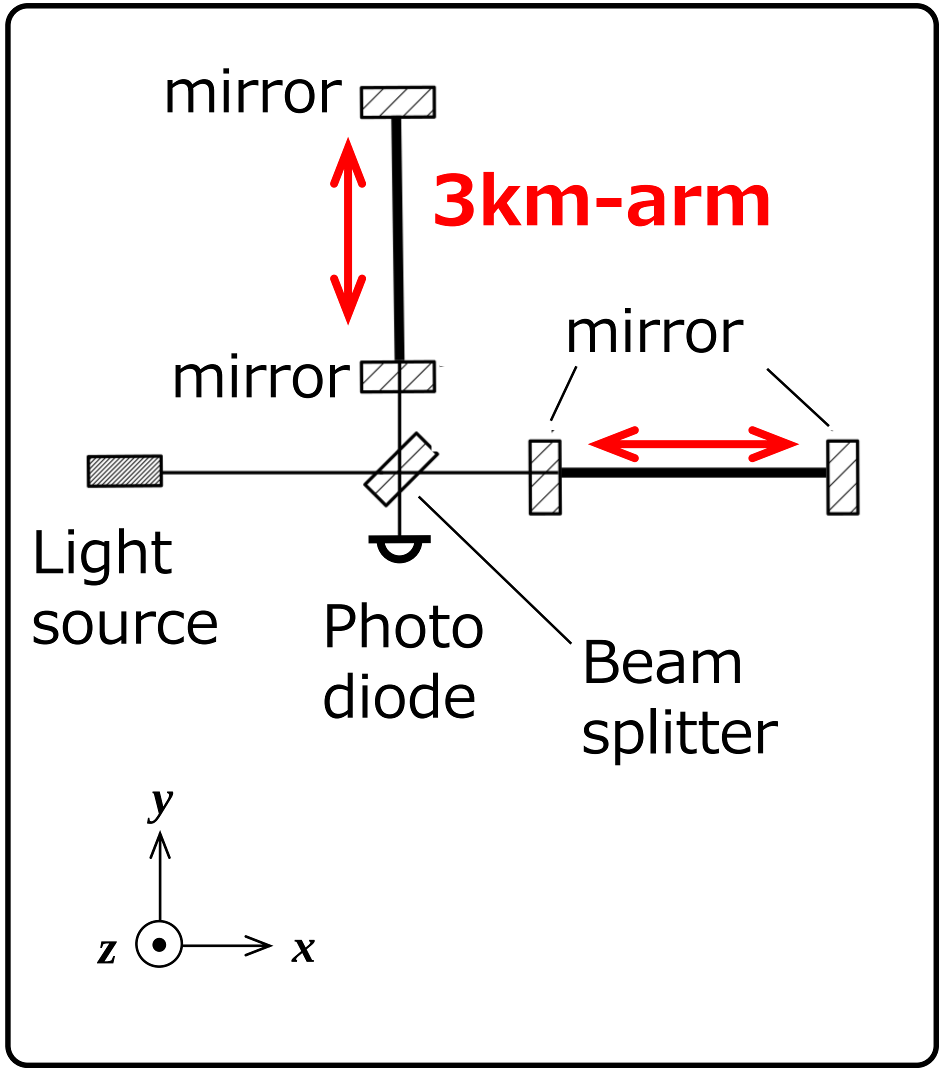
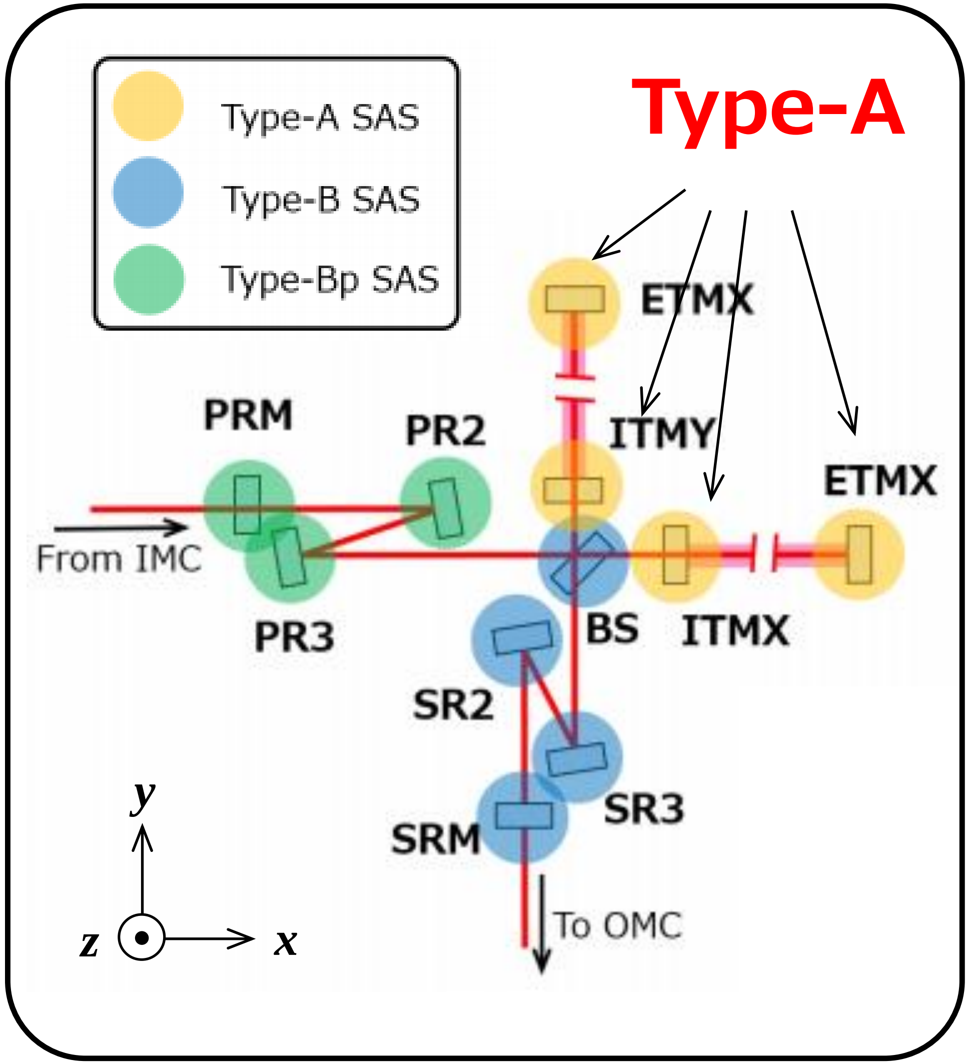
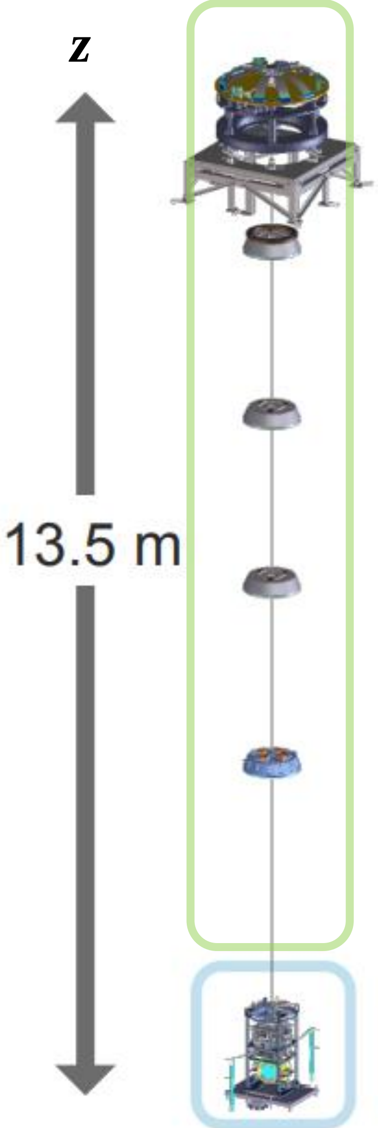
KAGRA detector





Type-A suspension:



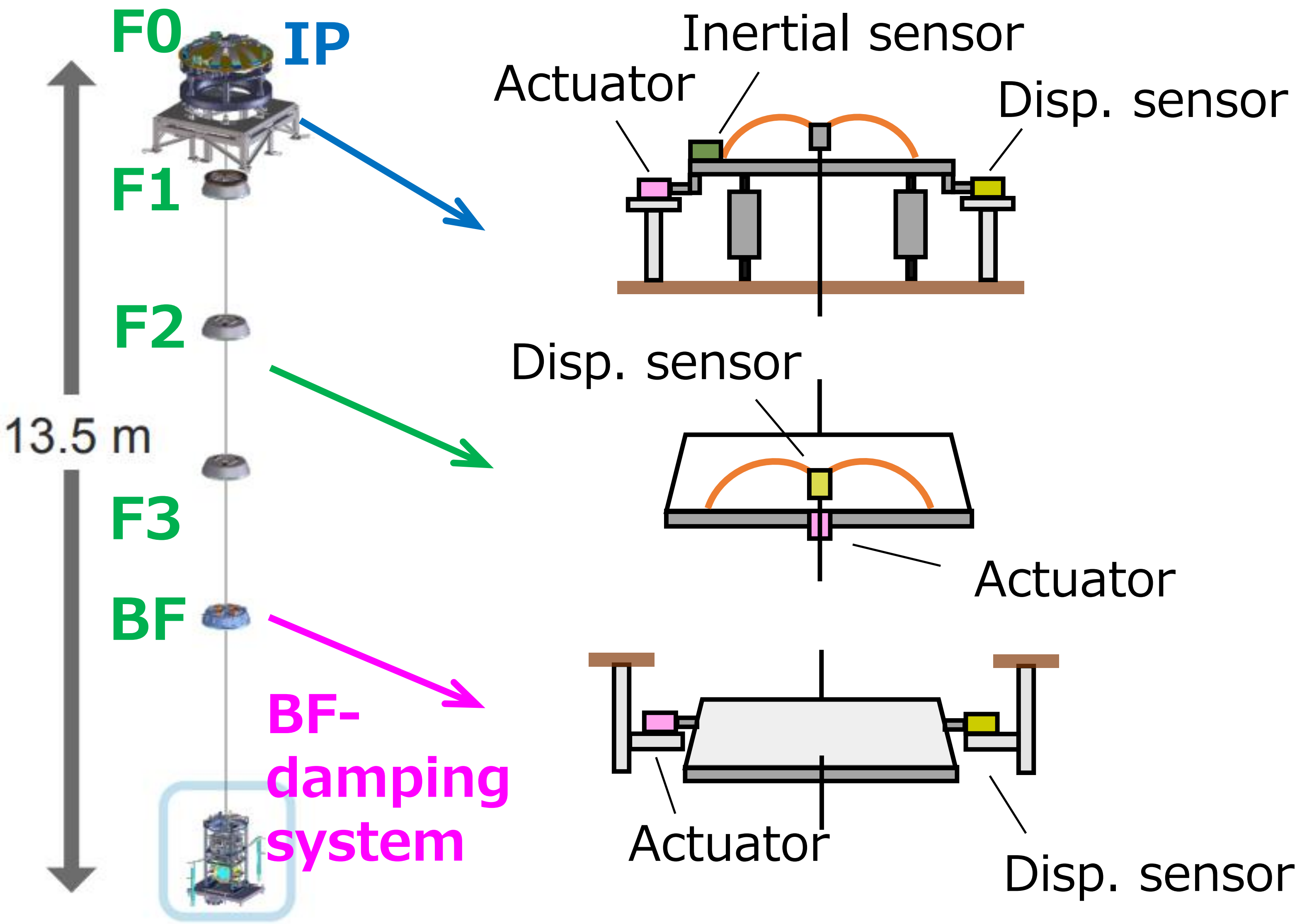


→ **The longest suspension in KAGRA**

- Upper 5 stages: room-temperature

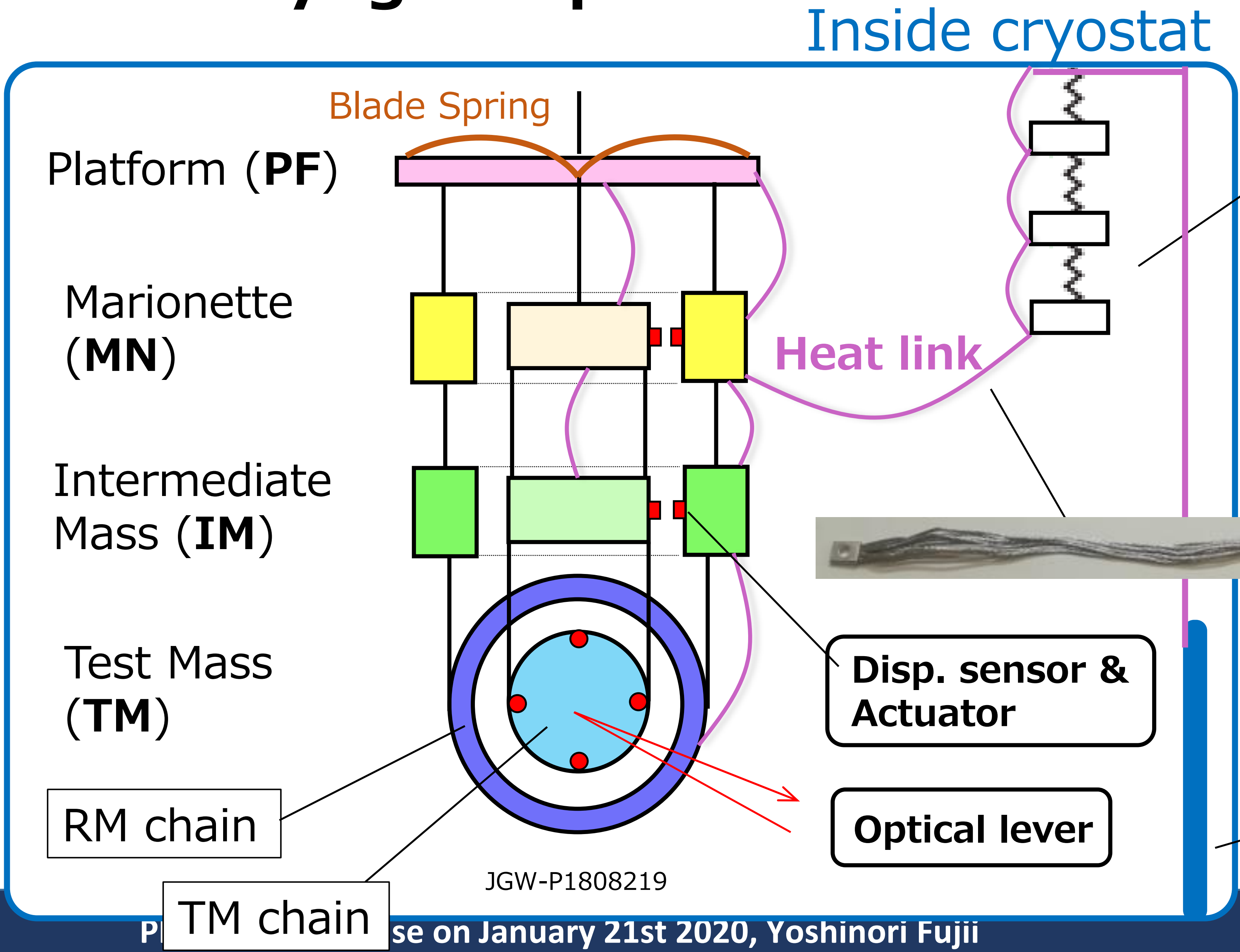
- Lower 4 stages: cryogenic-temperature

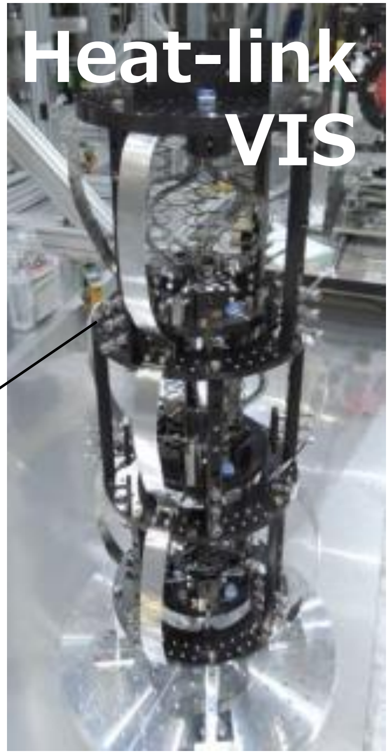
Components of room-temperature part:



* Inverted pendulum (IP)
* Vertical spring filters
* BF-damping system

Components of cryogenic part:





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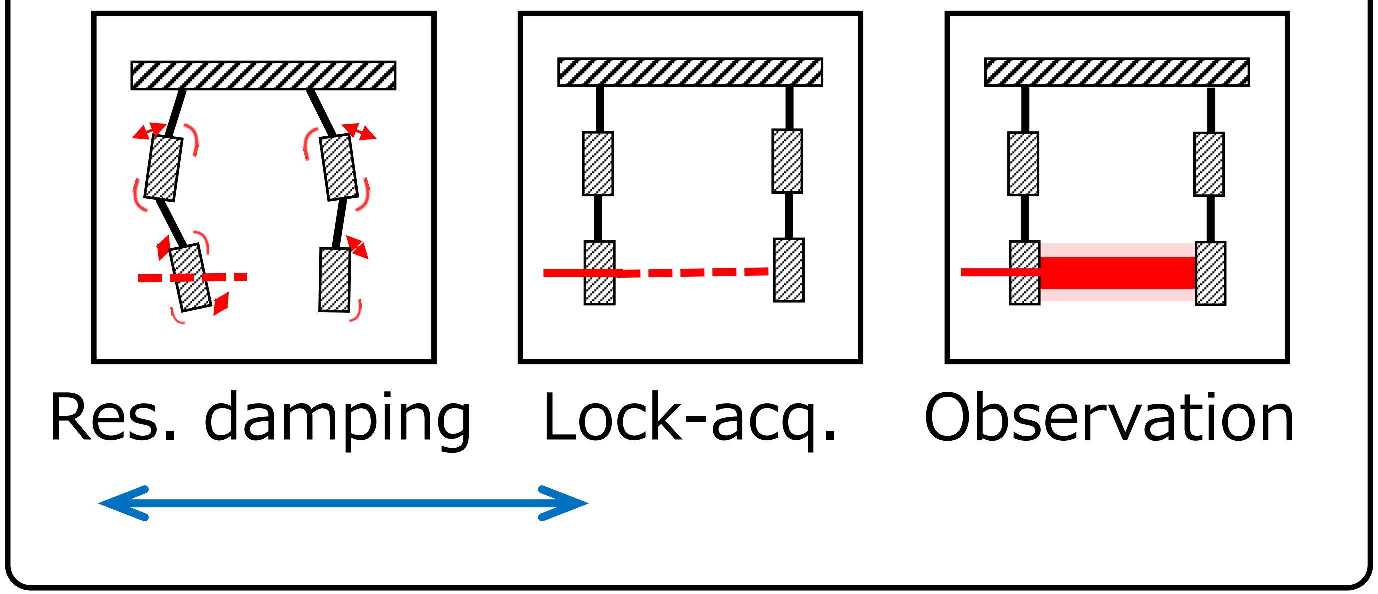
→ TypeA suspension controls toward lock acquisition

My work: Local control for full Type-A suspension

Interferometer control phases



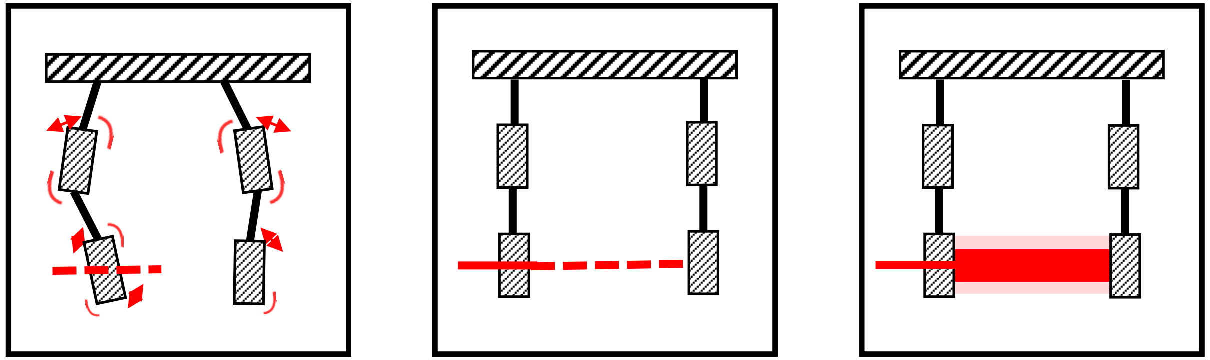
Goal:

To construct suspension local control system of full Type-A to allow interferometer locking.

- **Implementation**
- **Performance test**

My work: Local control for full Type-A suspension

Interferometer control phases



Res. damping ⟷ Lock-acq. | Observation

Data acq. system & digital system

Mechanical system

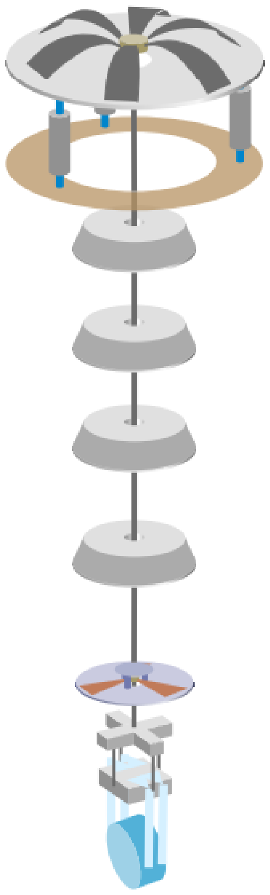
→ **Already done**

<u>Goal:</u>

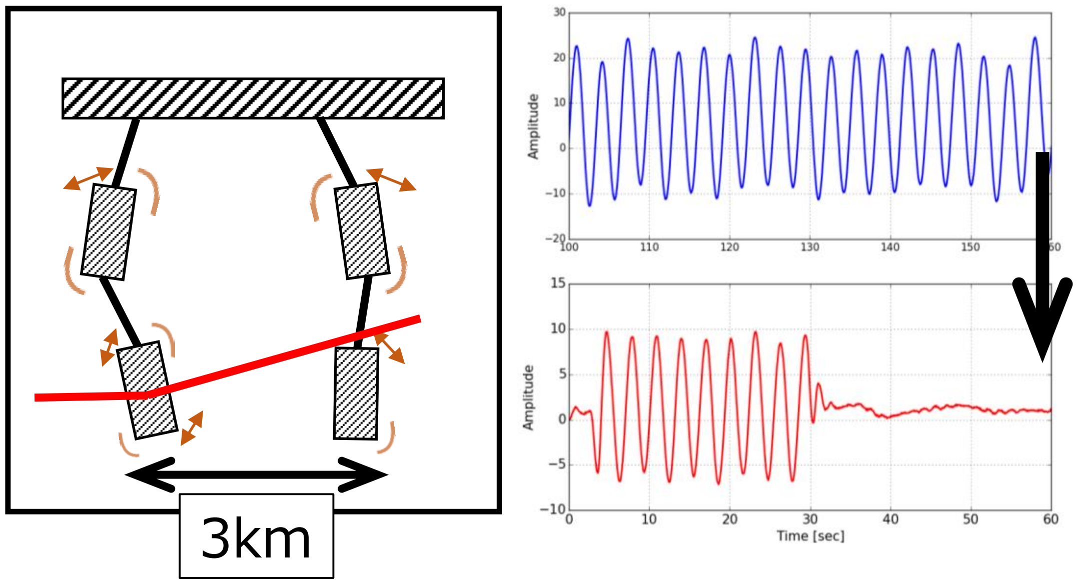
To construct suspension local control system of full Type-A to allow interferometer locking.

* Control system in observation (→ future work)

What is necessary for the local control toward lock acquisition:

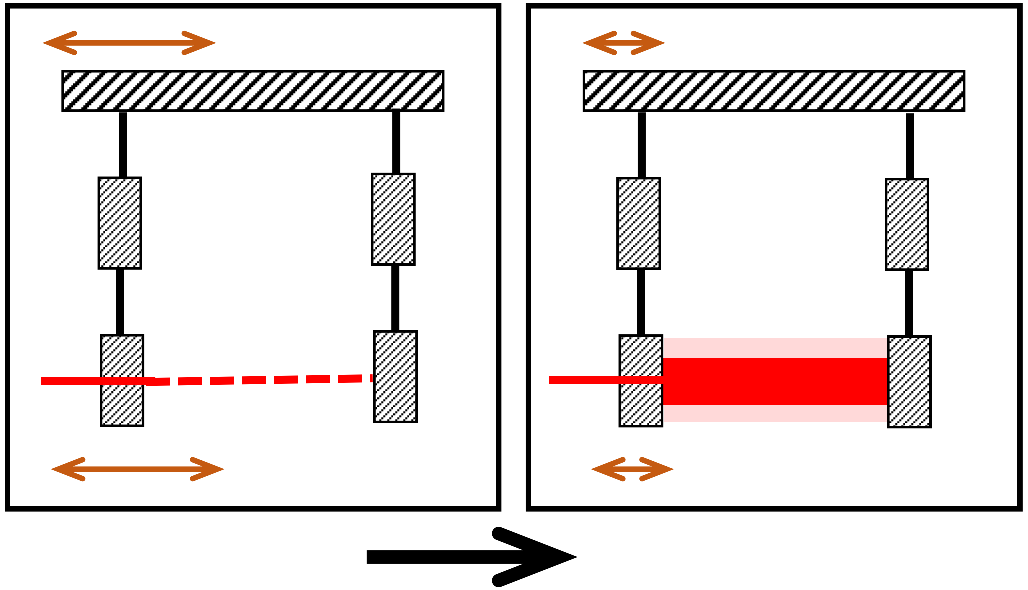


To damp resonances



→ Reduce lock loss time

To suppress mirror motion



→ Stable operation

What I did:

1. Frequency response check for mechanical system

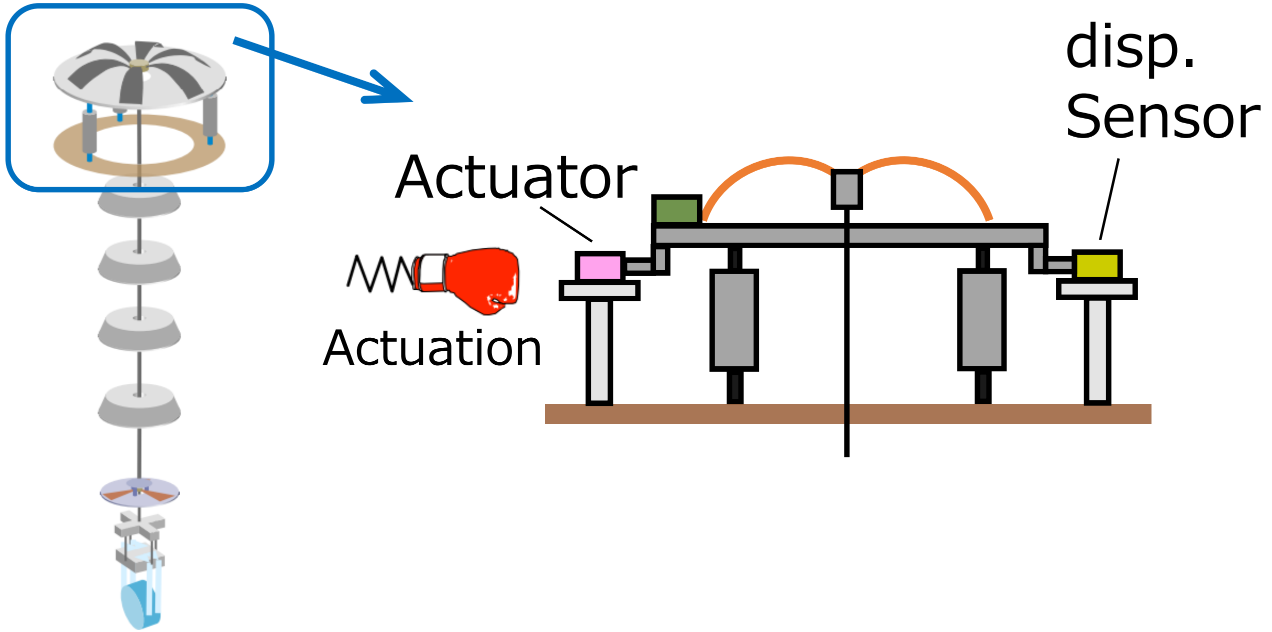
2. Resonance damping

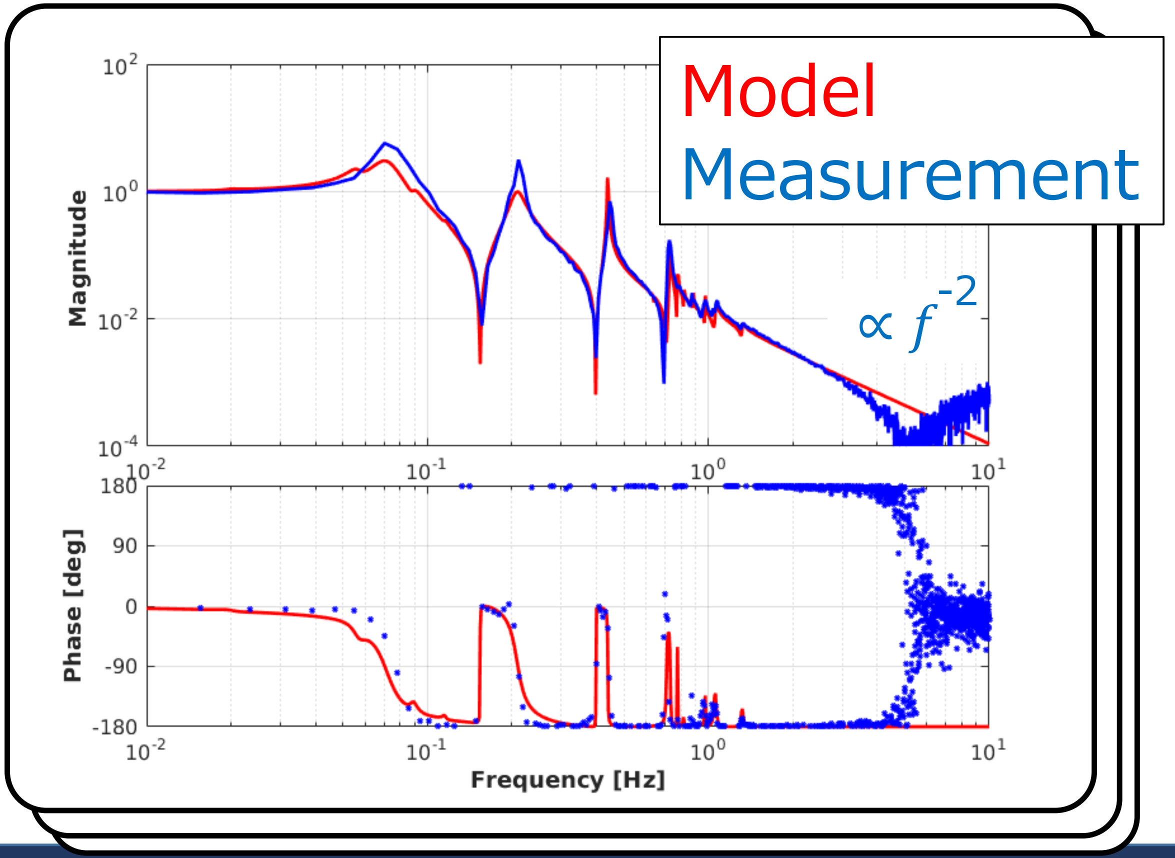
3. Mirror residual motion suppression

1. Frequency response check:

- **Target:** Confirm the system has characteristics of pendulum
- **Measurement:** Frequency responses from actuators to sensors

*** By each component**



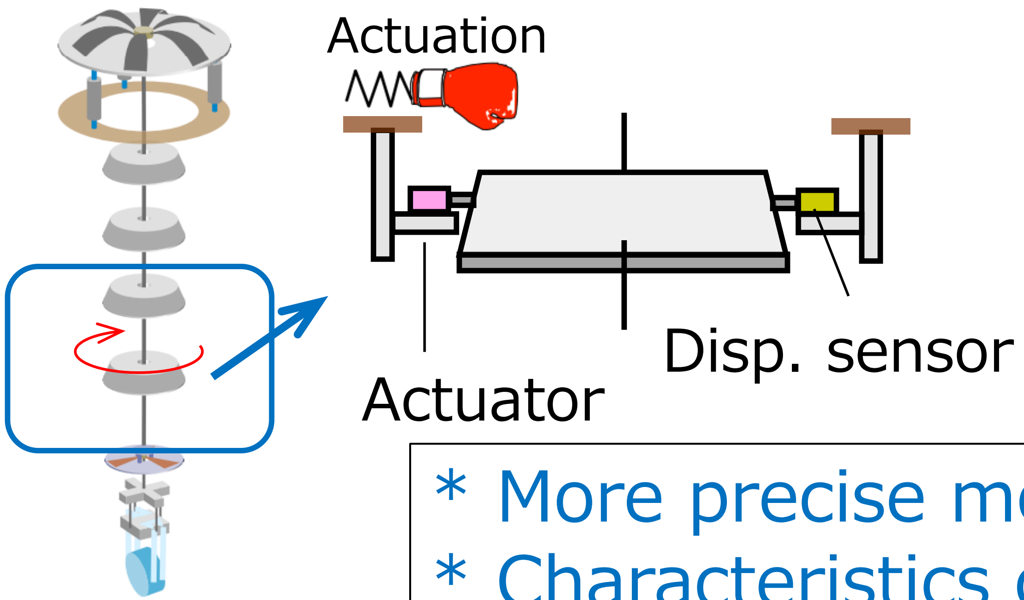


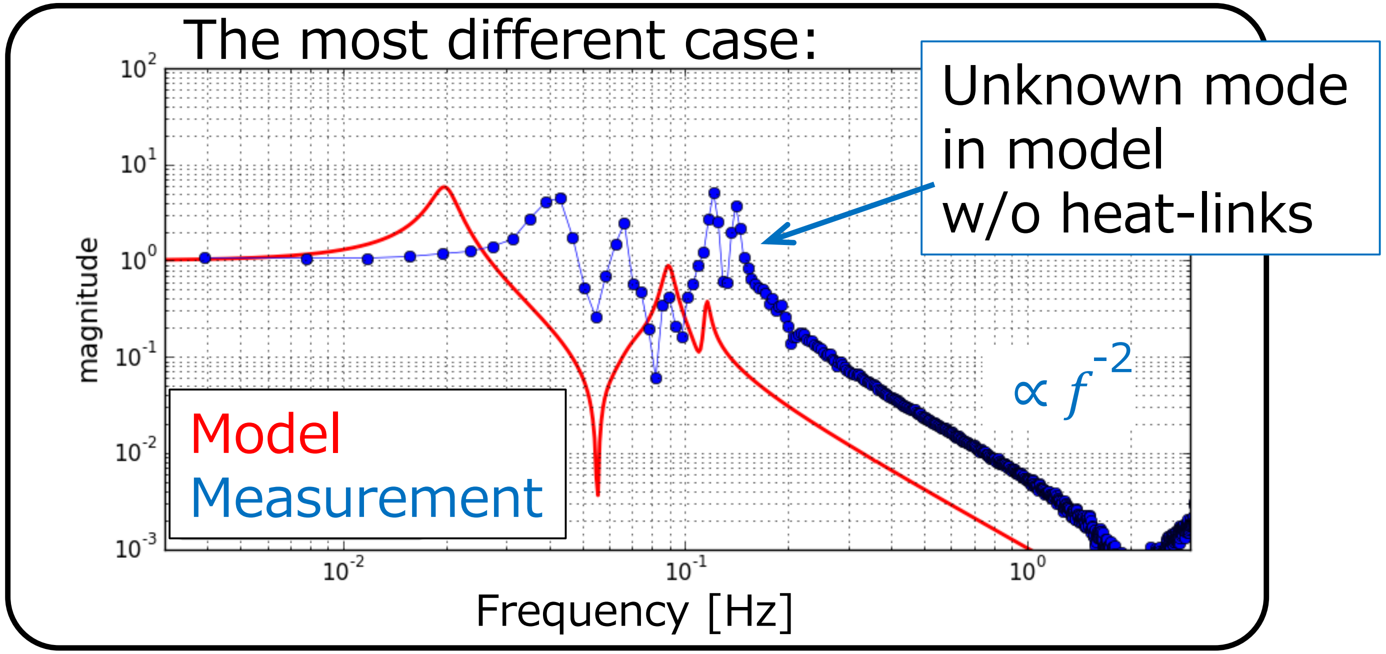
Model: 3D-rigod-body simulation

1. Frequency response check:

- **Target:** Confirm the system has characteristics of pendulum
- **Measurement:** Frequency responses from actuators to sensors

*** By each component**

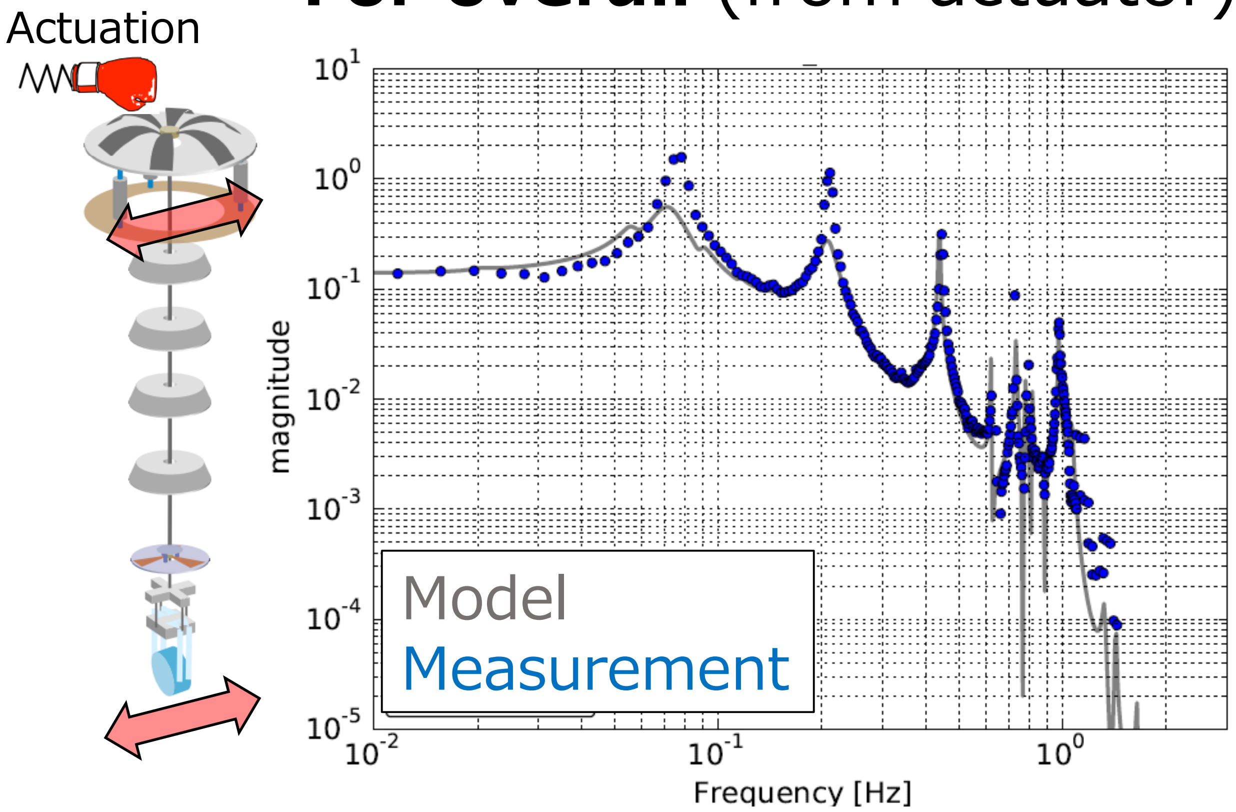


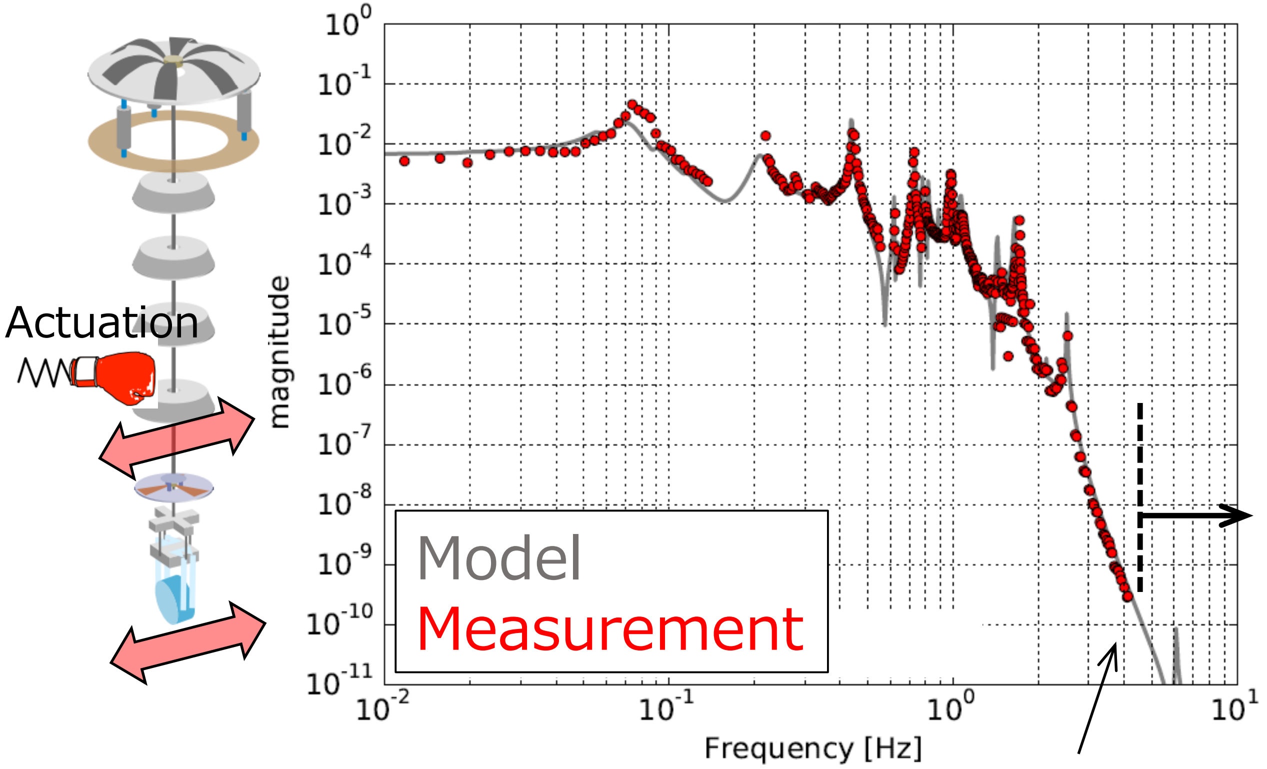


* More precise model tuning → Necessary
* Characteristics of pendulum
→ Okay to build control for lock acquisition

1. Frequency response check:

* **For overall** (from actuator)



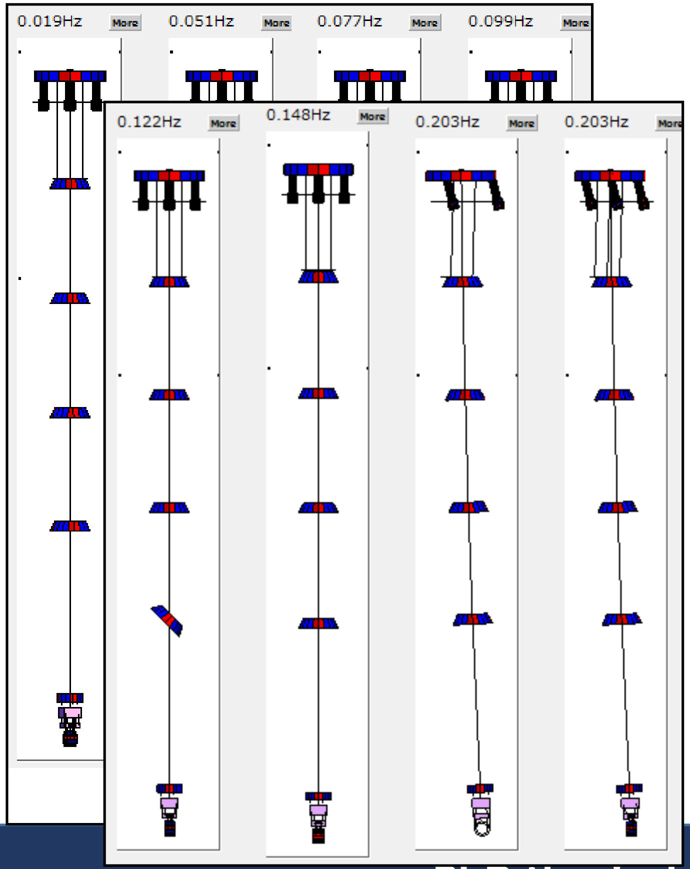


More sensitive interferometer is necessary.

→ For overall performance, (model tuning is also necessary though)
Type-A suspension has characteristics of pendulum up to 4.2 Hz.
→ Assuming extrapolation, disp. noise at 10 Hz is attenuated.

2. Resonance damping:

- **Target:** To damp all the resonances disturbing the lock acquisition, within 1 min as 1/e decay time.



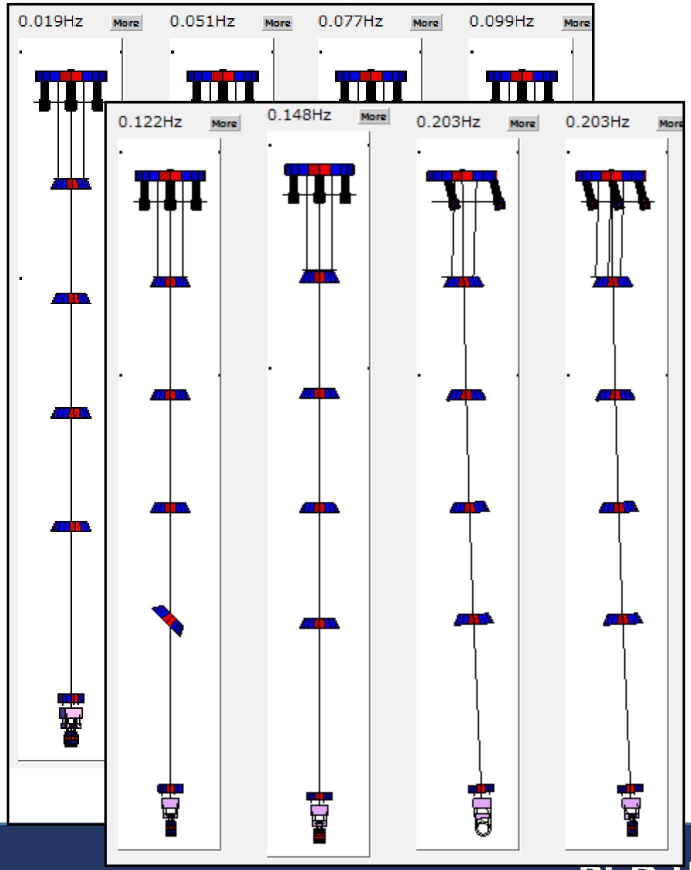
Number of resonances:

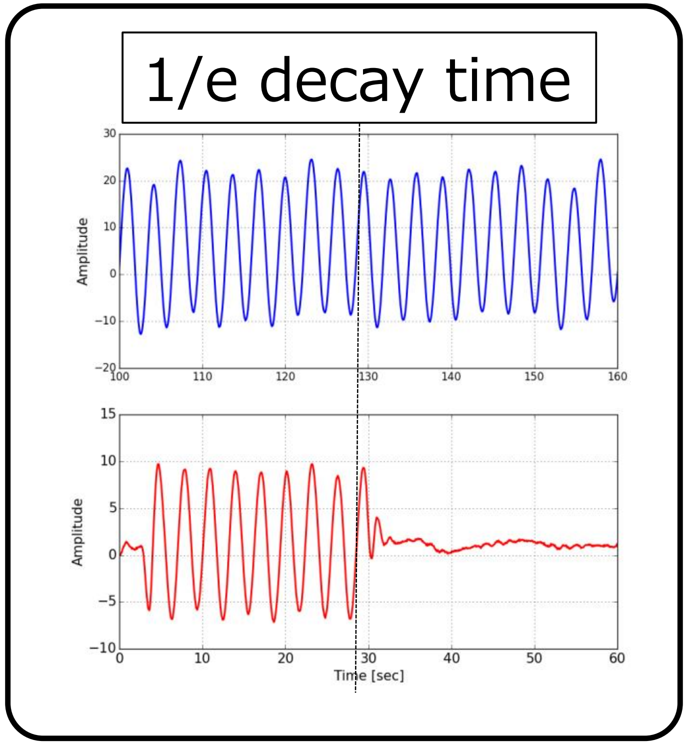
Assuming rigid-bodies
→ 75 modes

From sensor & actuator availability
Measured:
→ For 53 modes (res. frequency < 30Hz)

2. Resonance damping:

- **Target:** To damp all the resonances disturbing the lock acquisition, within 1 min as 1/e decay time.
- **Measurement:** 1/e decay time constant of each resonant mode



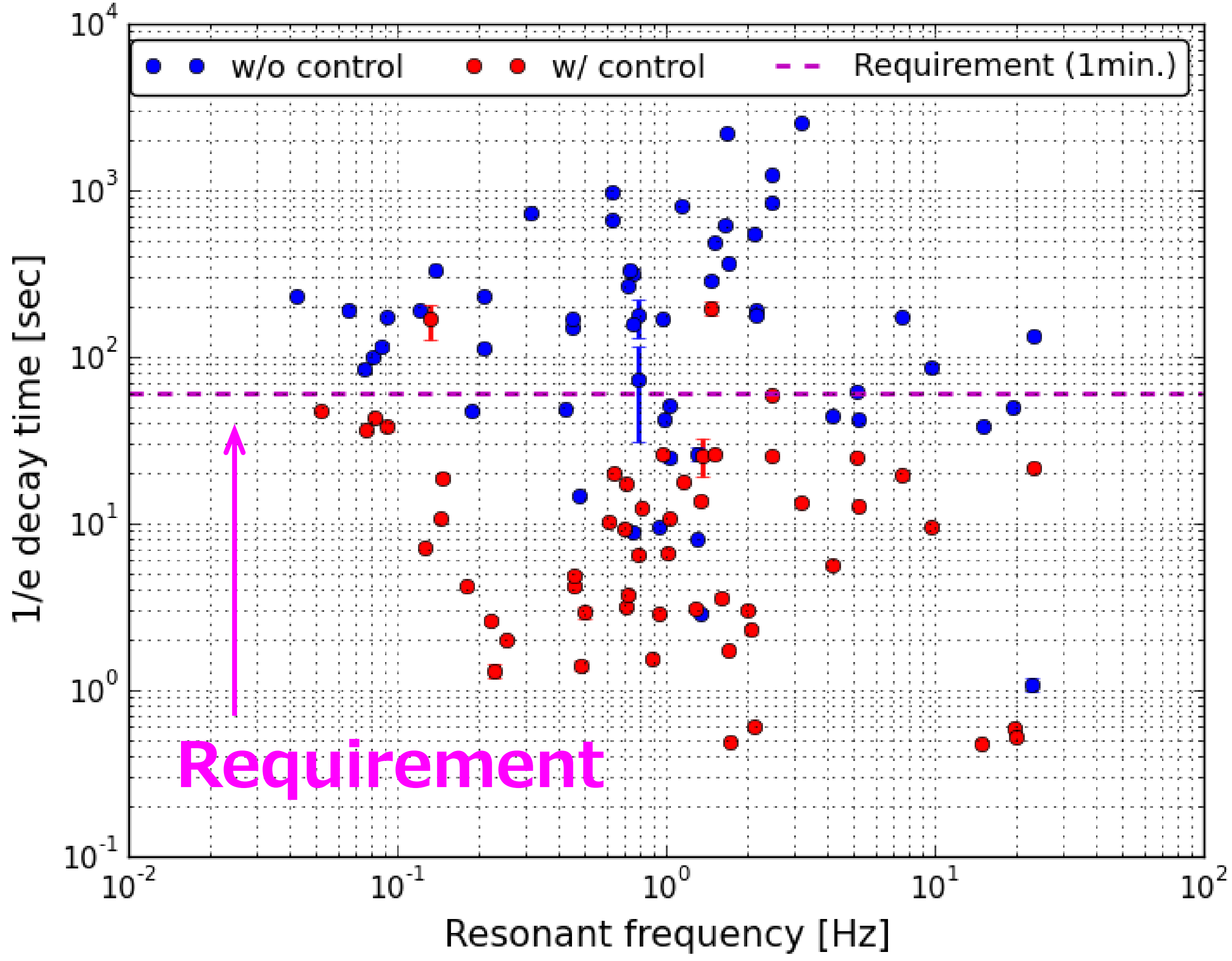


* Excite resonant mode one by one,

(as much as possible)

by sending a sinusoidal signal to implemented actuators.

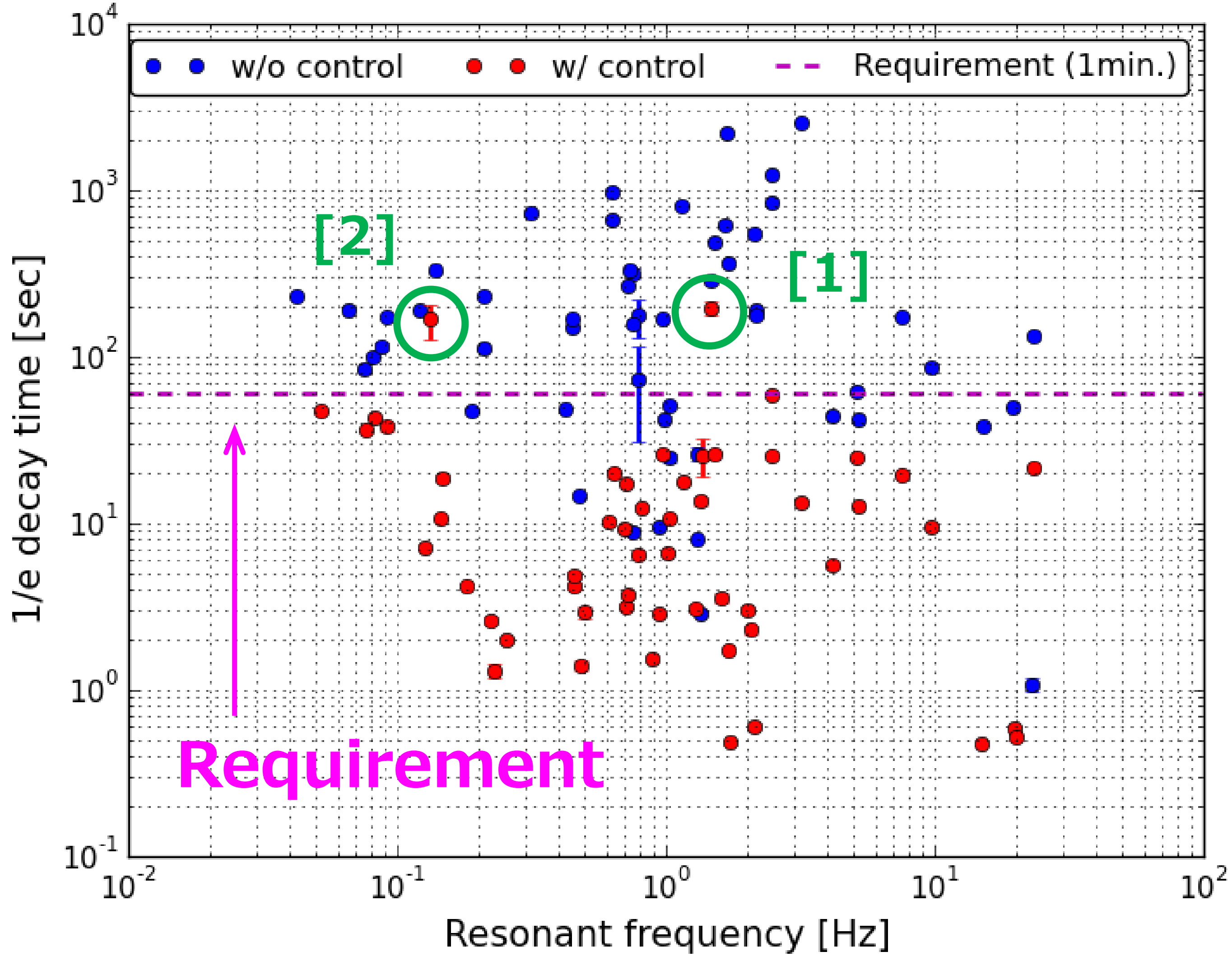
2. Resonance damping:



w/o control

w/ control

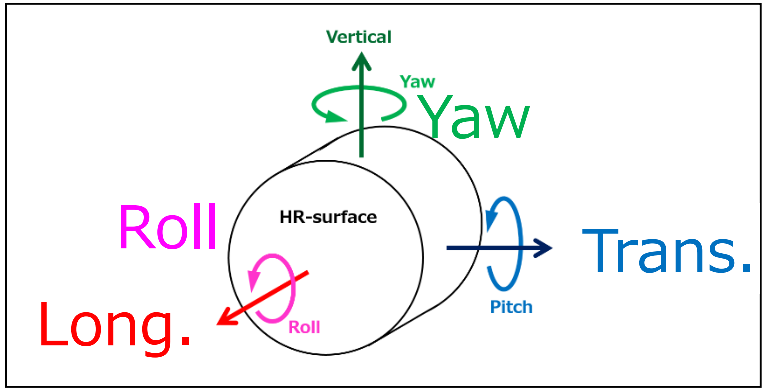
2. Resonance damping:



[1] #43: **1.5Hz**

Roll / Trans. motion

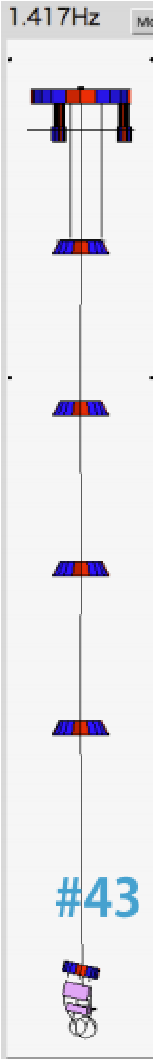
→ Not disturbs the lock acquisition.



[2] 0.14Hz

unknown Yaw motion

→ The model w/o heat-link system failed to predict.



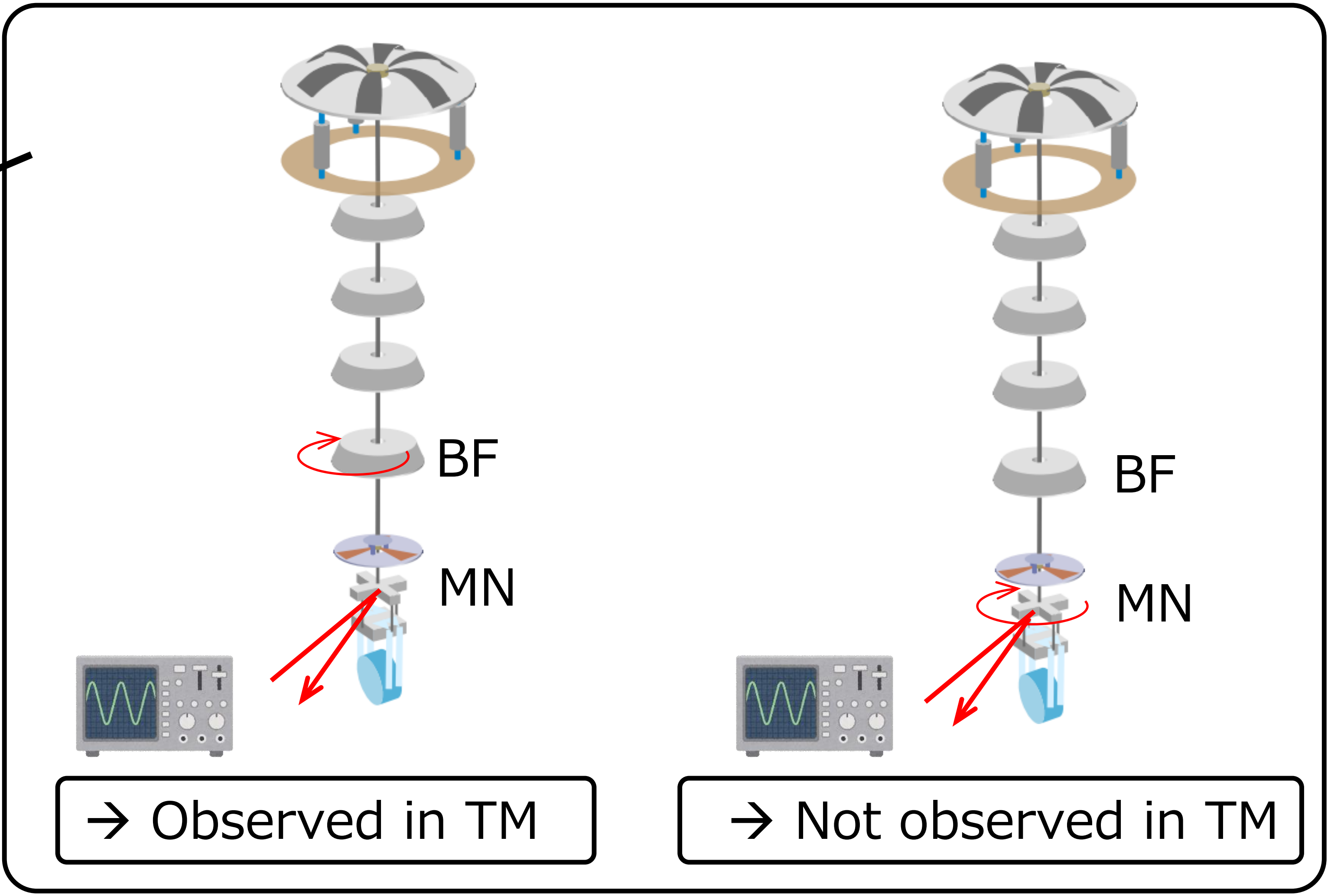
2. Resonance damping:

[2] 0.14Hz mode

1. This will be excited when BF-stage actuated.

2. for interferometer control: only payload is controlled.

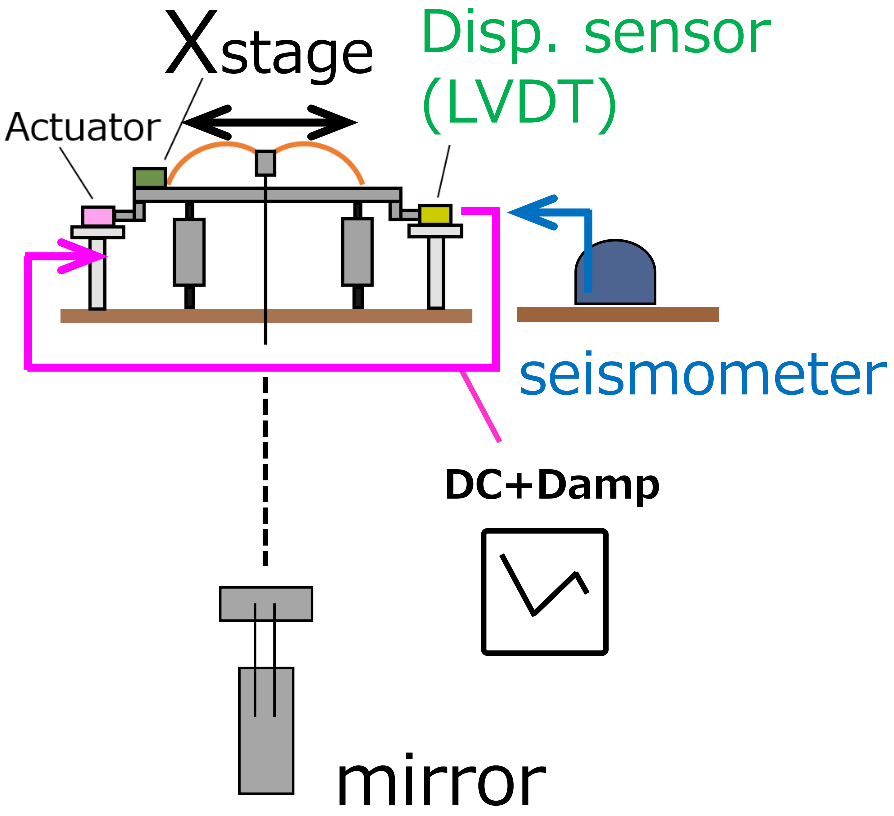
→ This mode will NOT be excited at lock loss.



→ The control system damps all the resonances disturbing the lock acquisition **for the lock-recovery mode**.

3. Mirror residual motion suppression:

- **Target:** To suppress mirror velocity & displacement so that the interferometer lock is acquired.



$$X^{virtual}_{sensor} = [\, \underbrace{X_{stage} - X_{ground}}_{\text{Displacement sensor signal}} + \underbrace{X^{seis}_{ground}}_{\text{Seismomter signal}} \,]$$

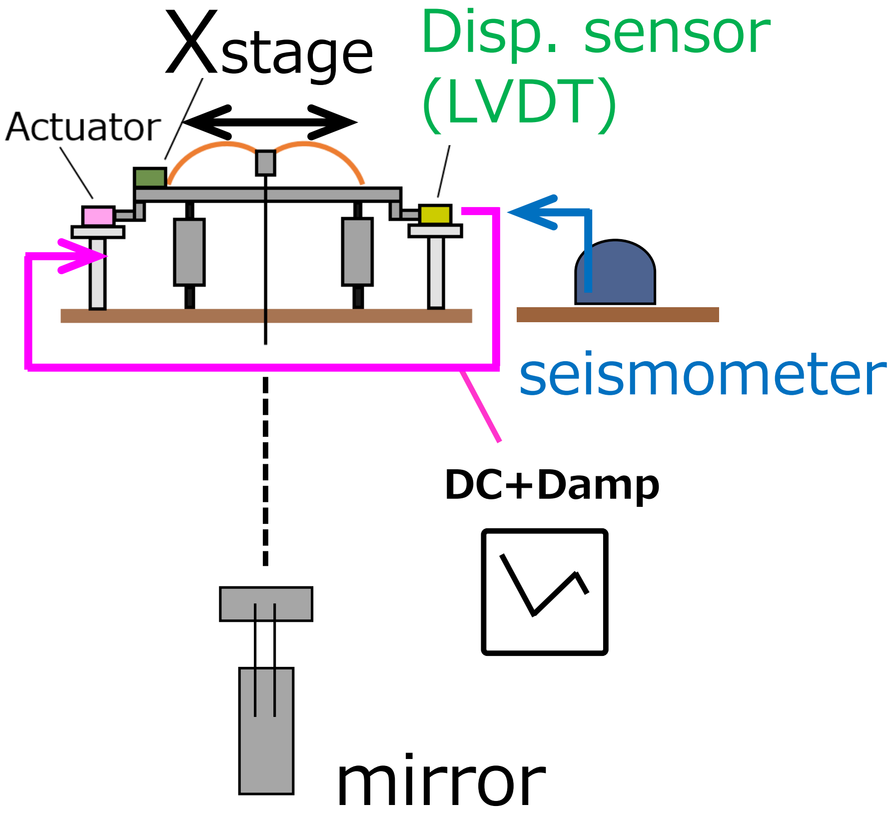
Displacement sensor signal

Seismomter signal

→ Cut the seismic noise injection via disp. sensor. (→ sensor correction)

3. Mirror residual motion suppression:

- **Target:** To suppress mirror velocity & displacement.
- **Measurement:** Frequency response from ground to mirror



$$X^{virtual}_{sensor} = [\, \underline{X_{stage} - X_{ground}} \,] + \underline{X^{seis}_{ground}}$$

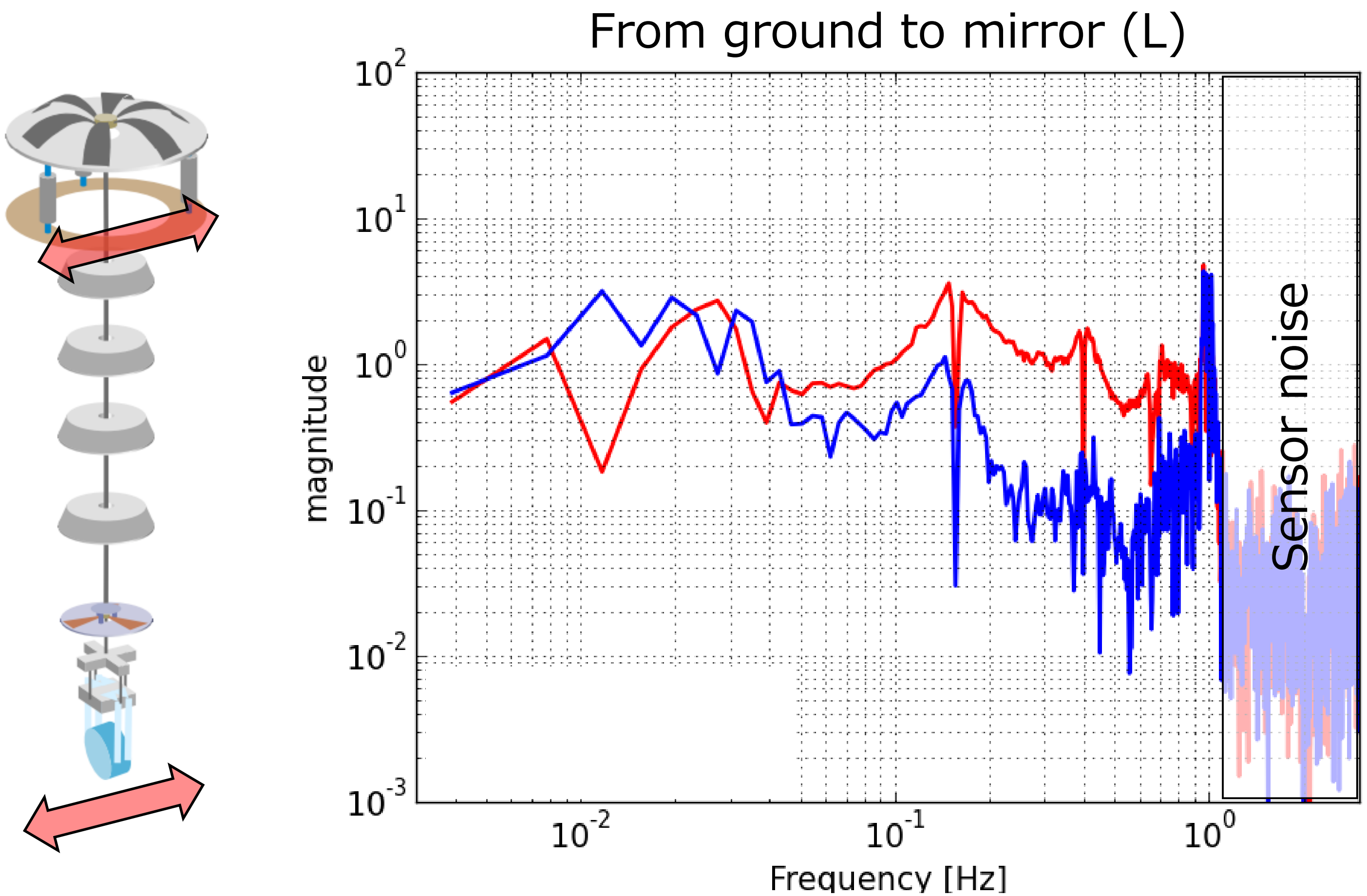
Displacement sensor signal

Seismomter signal

→ Cut the seismic noise injection via disp. sensor. (→ sensor correction)

3. Mirror residual motion suppression:

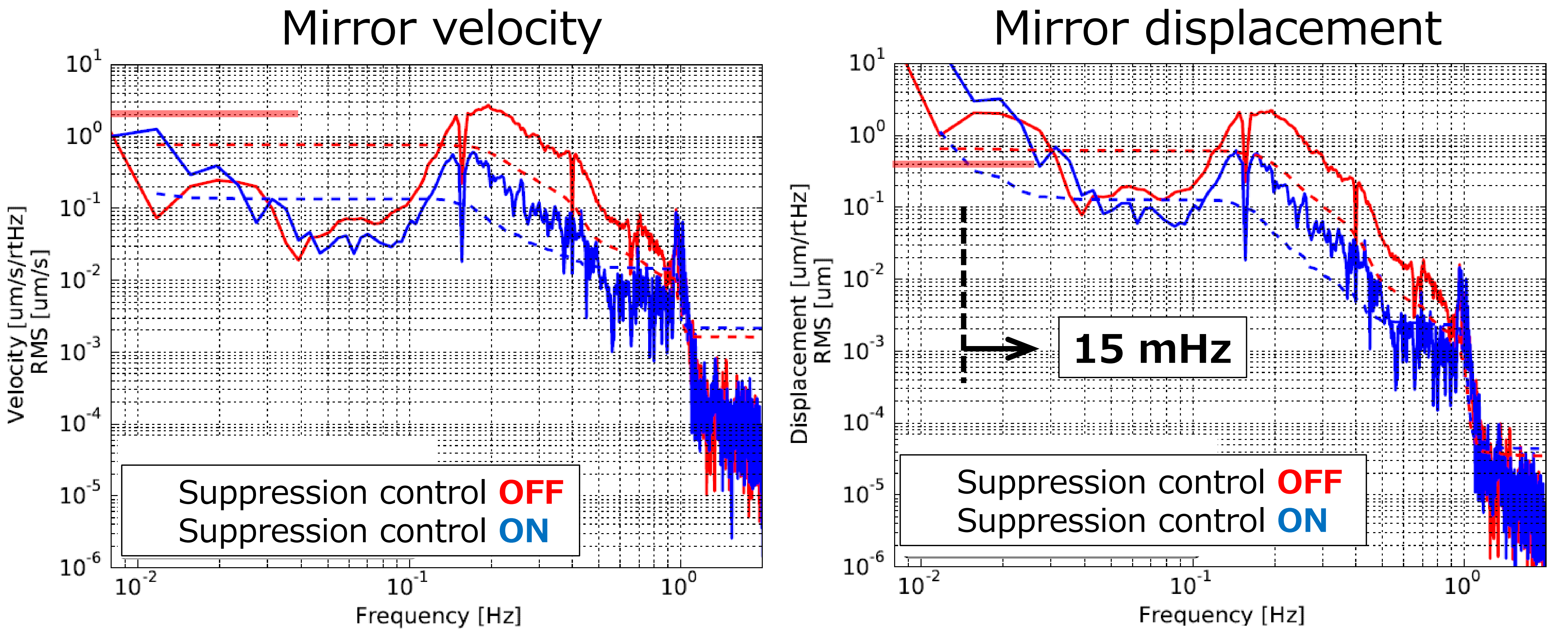
* Frequency response from ground to mirror



w/o sensor correction

w/ sensor correction

3. Mirror residual motion suppression (w/ 90%tile seismic motion)



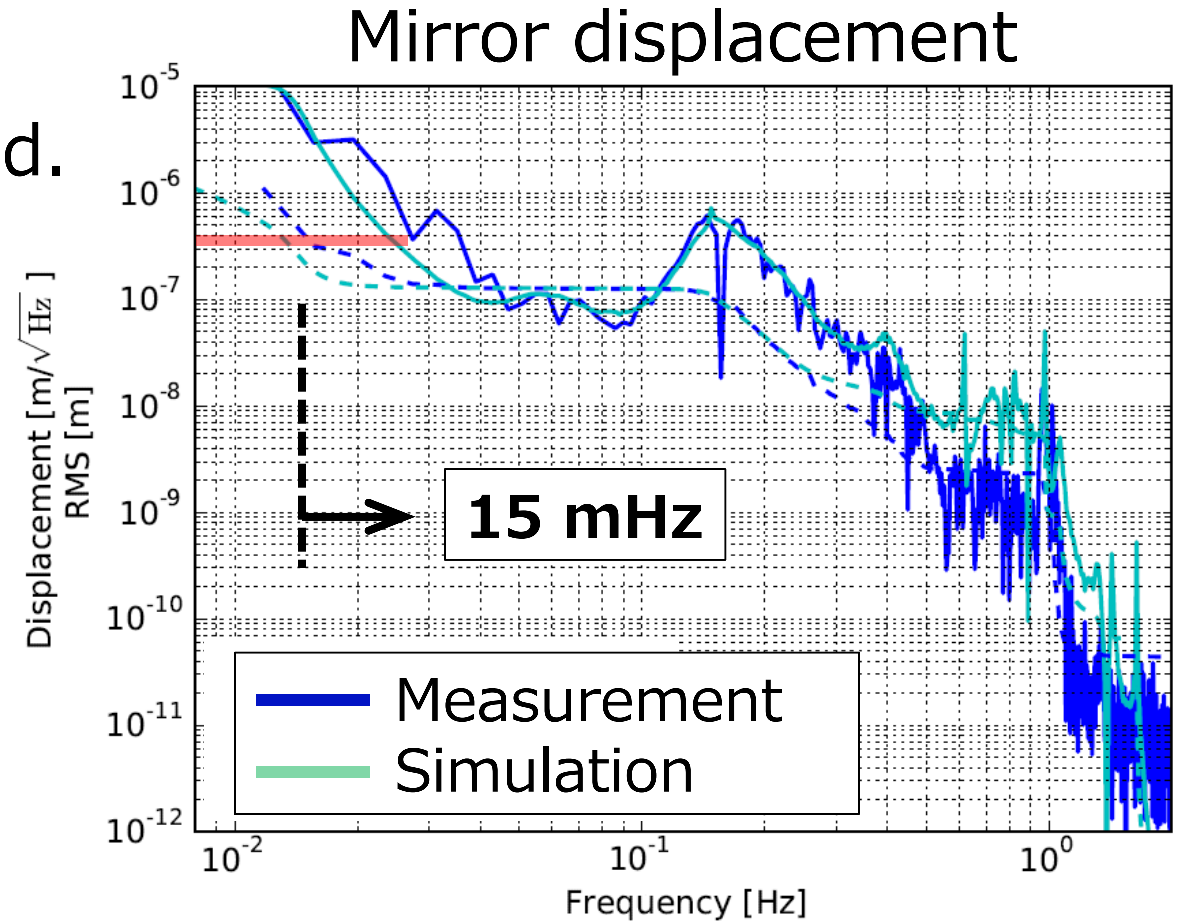
→ The control system locally suppresses the residuals and satisfies the requirement for in the time scale of 1 min.

3. Mirror residual motion suppression (w/ 90%tile seismic motion)

* Measurement agrees with simulation. → works as designed.

* Performance at < 15 mHz:
→ due to noise coupling from seismometers.
→ For further stabilization,
1. local seismometer corr. system (with tilt-meter), or
2. global control with interferometer signal

is necessary. → **Task of the observation phase control.**



→ Local control system for lock acquisition has been realized.

Summary: performance of local control system

1. Frequency response check
   → Type-A suspension has characteristics of pendulum.
     → the unexpected frequency response → further model tuning.
       → Enough for lock acq. phase control.

2. Resonance damping
   → The control system damped all the resonances disturbing the lock acquisition for the lock-recovery mode within 1min in 1/e decay time.

3. Mirror residual motion suppression
   → The control system locally suppresses the residual mirror motion in the time scale of 1 min.

→ Local control system for lock acquisition has been realized.

This is the first time to control KAGRA full Type-A suspension.

Summary of this research:

1. **Fast localization simulation by current network with hierarchical approach**

   → If V (K) sensitivity > 0.2 (0.28) of LIGO,
   the hierarchical search improves the fast localization performance in the heterogeneous network using existing low-latency infrastructure.

2. **TypeA suspension controls toward lock acquisition**

   → I've constructed local control system for full Type-A suspension of KAGRA toward acquiring interferometer lock.

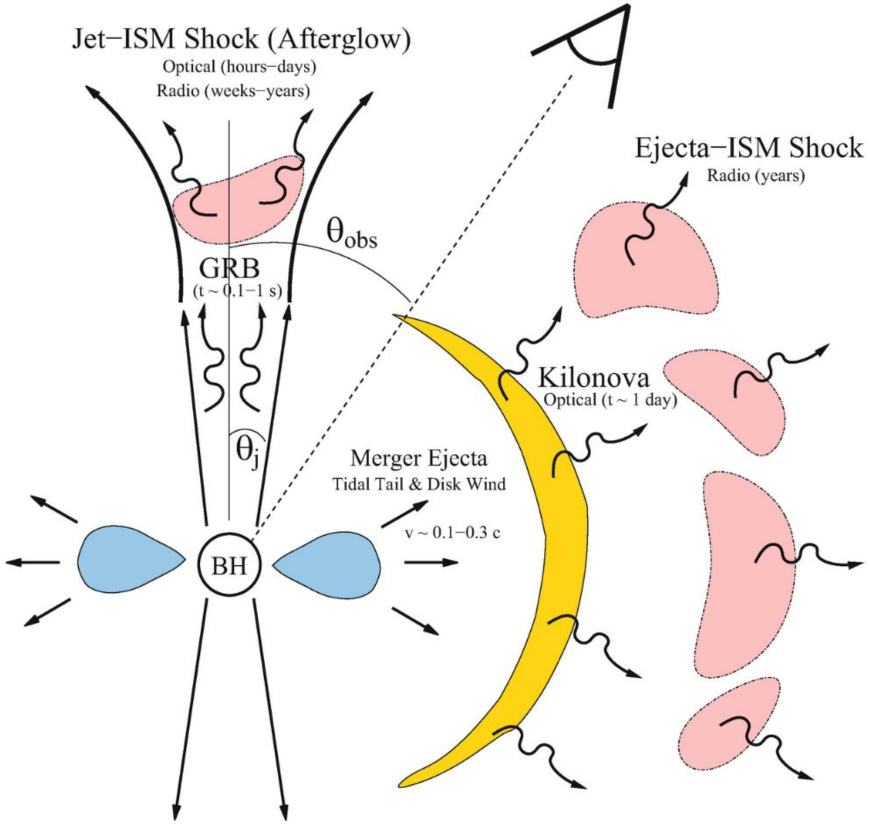
> **→ This contributes to KAGRA joining to the network as the 4th detector.**

Backups

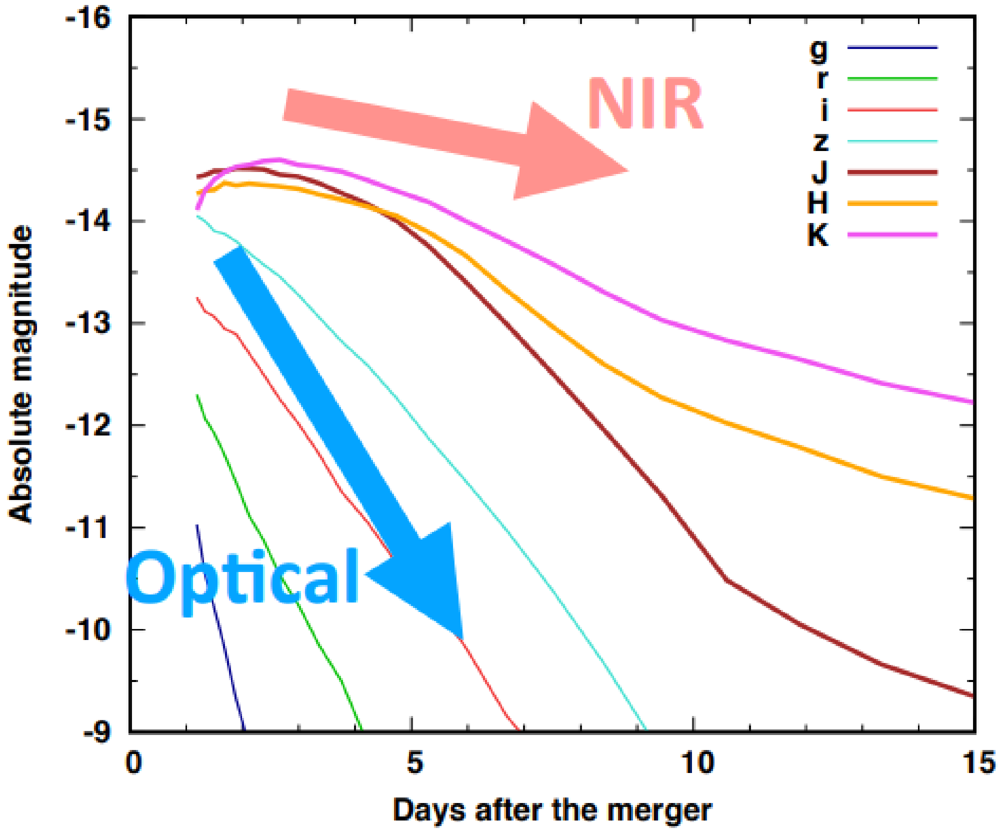
Note: fast localization

Kilonova: Electromagnetic emission powered by radioactive decays of r-process nuclei, given by ejected material from neutron star mergers.

[ref] https://iopscience.iop.org/article/10.3847/1538-4357/aaa0cb/pdf



Metzger & Berger 2012

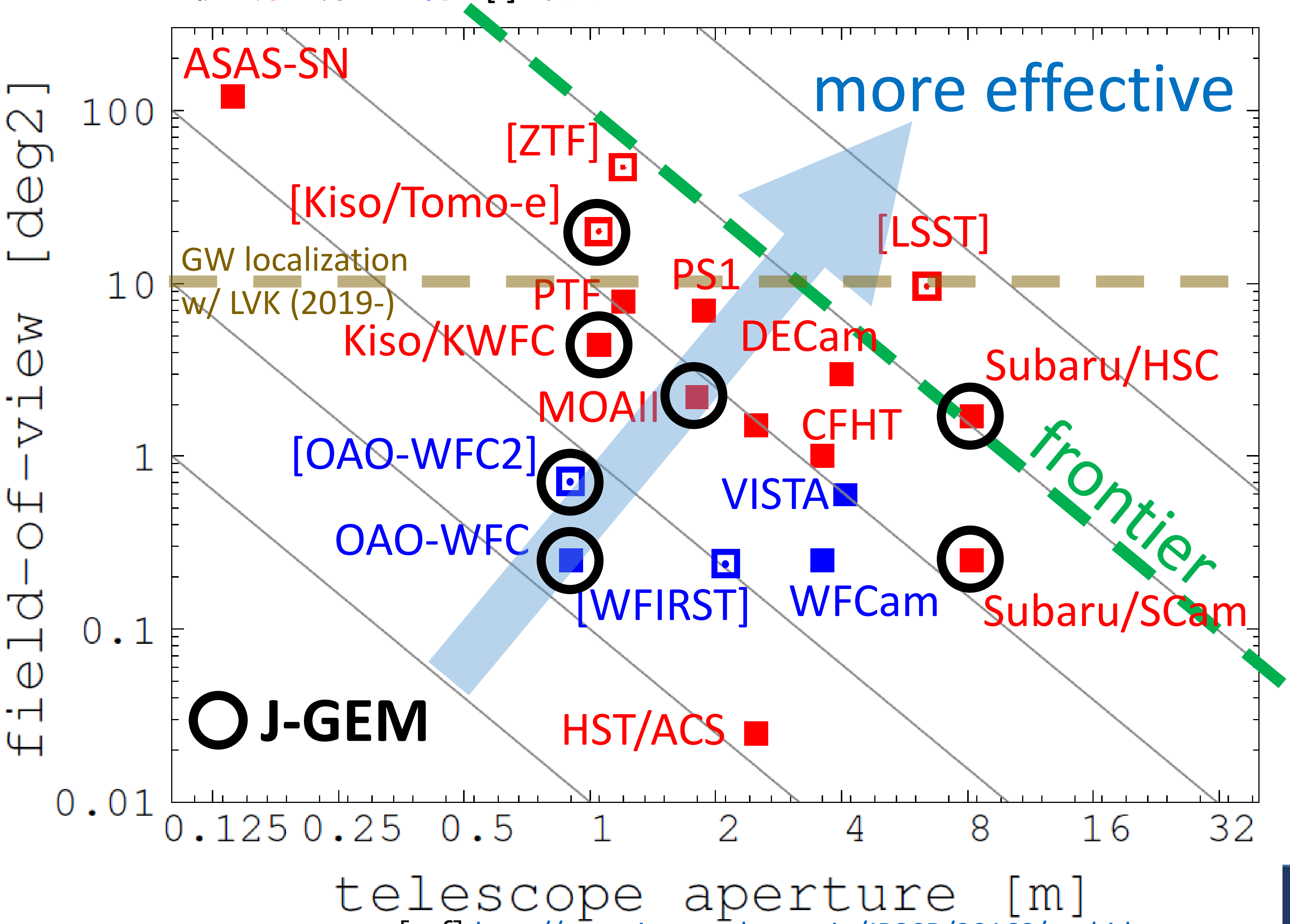


http://www.icehap.chiba-u.jp/activity/180326MultiMessenger/3-26/tanaka_20180326.pdf

FOV vs. Area by GWs

世界の可視近赤外広視野望遠鏡・装置

可視:赤　赤外:青　[ ]:将来計画



[ref] http://www.icrr.u-tokyo.ac.jp/JPSCR/2016S/yoshida.pptx

Detector response:

The signal (I)

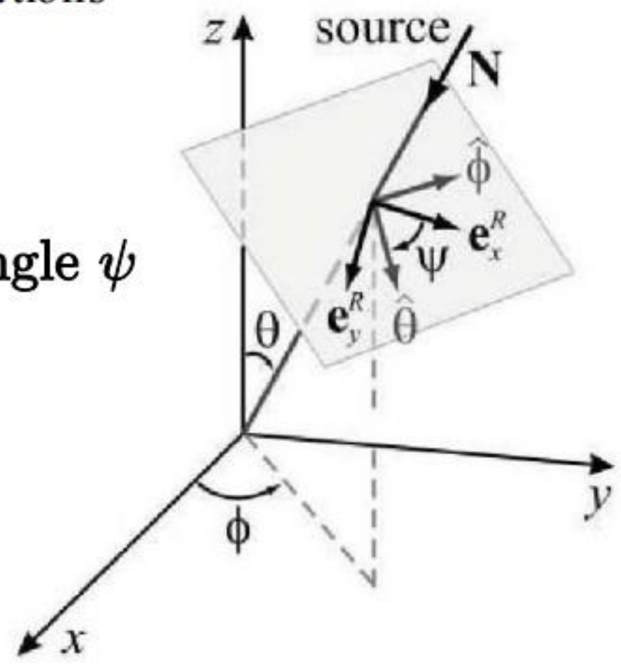
Signal sensed by detector is a combination of two polarizations

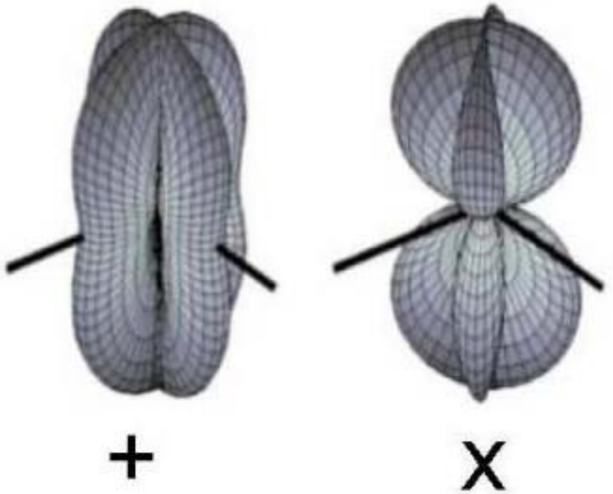
$$h(t) = F_+(\theta,\phi,\psi)\, h_+(t) + F_\times(\theta,\phi,\psi)\, h_\times(t)$$

F_+ and $F_\times$: detector response functions
depend on sky location (θ,ϕ) and polarization angle ψ

$$F_+ = -\tfrac{1}{2}(1+\cos^2\theta)\cos 2\phi \cos 2\psi - \cos\theta \sin 2\phi \sin 2\psi$$

$$F_\times = \tfrac{1}{2}(1+\cos^2\theta)\cos 2\phi \sin 2\psi - \cos\theta \sin 2\phi \cos 2\psi$$



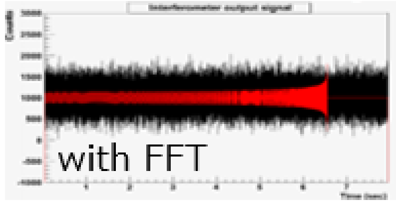


F_+ and $F_\times$ can be approximated as constant over length of CBC signals in ground based detectors

Ref: http://old.apctp.org/conferences/2011/NRG2011/NRGPDF/CBC_DA_Korean_School_2011.pdf

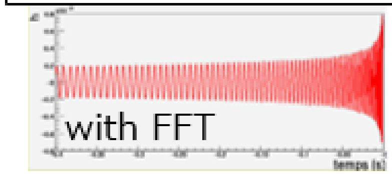
Matched filtering

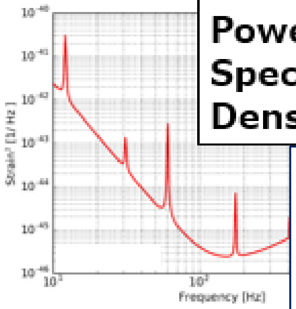
Detector output



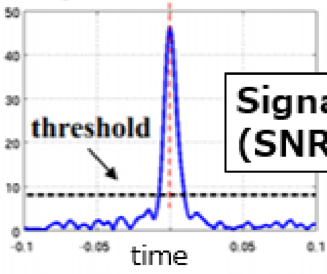
×

Theoretical waveform (Template)





Noise Power Spectrum Density



Signal-to-Noise ratio (SNR)

JGW-P1707567

We introduce the reference time t_c as the time of the coalescence. We can rewrite the template (that is, normalized waveform) centering on t_c as $u(t;t_c) = u'(t - t_c)$. Thus,

$$\begin{aligned}\tilde{u}(f) &= \int_{-\infty}^{\infty} u'(t - t_c) e^{-2\pi i f t} dt \\ &= \int u'(t') e^{-2\pi i f t'} e^{-2\pi i f t_c} dt' \\ &= \tilde{u}'(f) e^{-2\pi i f t_c} ,\end{aligned}$$

where we assume $t = t' + t_c$ and $\tilde{u}'(f)$ is

$$\tilde{u}'(f) = \int u'(t) e^{-2\pi i f t} dt = \int u(t; t_c = 0) e^{-2\pi i f t} dt = \tilde{u}(f; t_c = 0) .$$

As a result, Eq.(2.10) can be rewritten as

$$(x, u) = 4\mathrm{Re} \int_0^{\infty} \frac{\tilde{x}(f)\tilde{u}^*(f; t_c = 0)}{S_n(|f|)} e^{2\pi i f t_c} df . \qquad (2.11)$$

Because this formula is equivalent to the inverse Fourier transformation from f to t_c, we can obtain the time series of (x, u) for each t_c by the inverse Fourier transformation. The calculation of Eq.(2.11) can be done efficiently with the Fastest Fourier Transform, such as FFTW.

SNR maximization:

Matched filtering in practice (II)

- The phase of the chirp signal is unknown

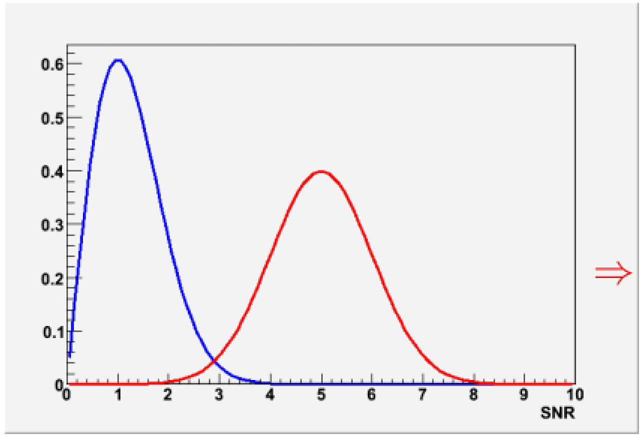
$$h(t) = A\,[h_c(t)\cos\Phi + h_s(t)\sin\Phi]$$

cosine and sine phases of the waveform

» The SNR has to be maximized over all possible values of Φ

Filter with T_{0° and T_{90° and take quadratic sum

$$S^2 = \sqrt{{S_{0^\circ}}^2 + {S_{90^\circ}}^2}$$



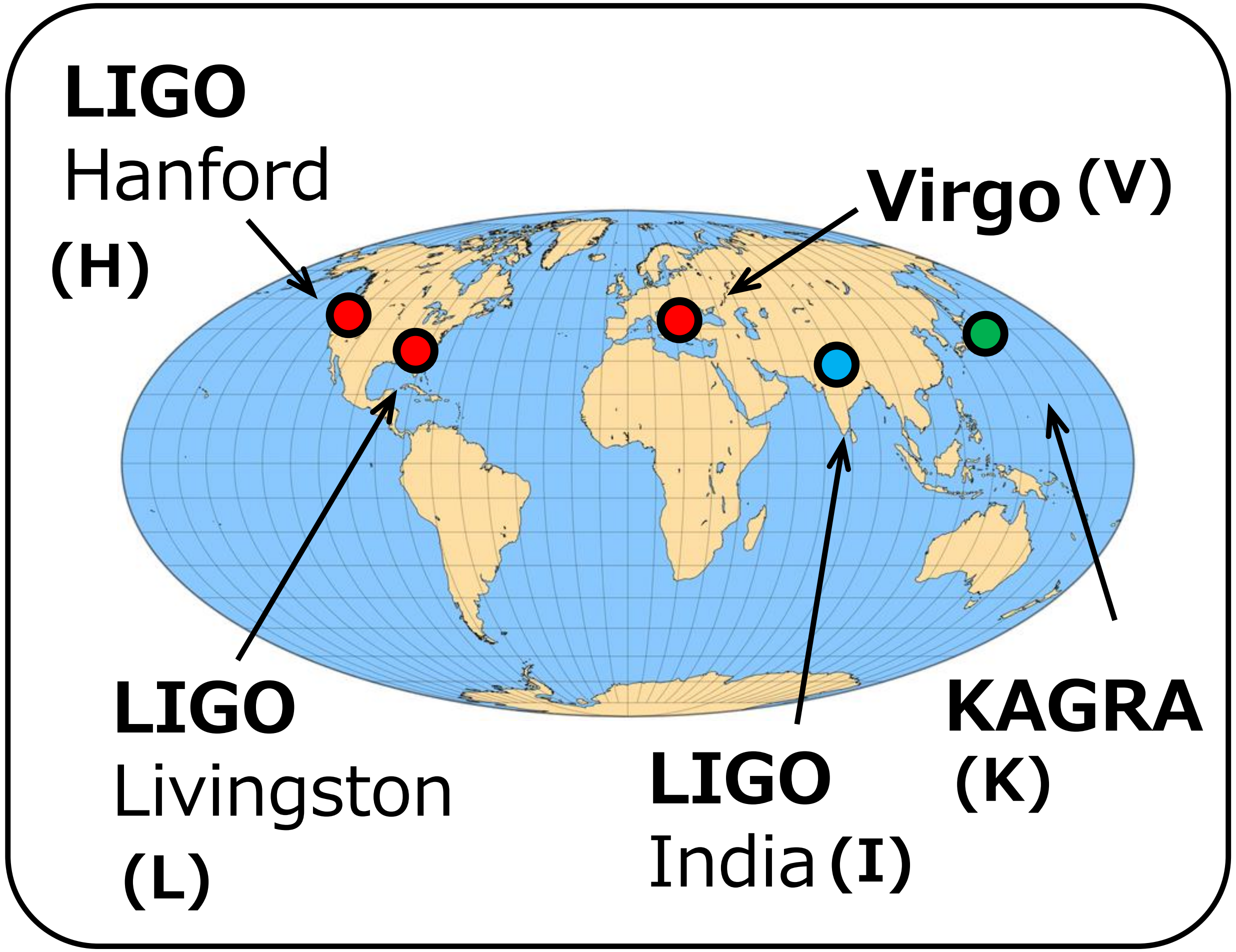
Noise has a χ^2 distribution
with 2 degrees of freedom $p(\rho) = \rho e^{-\rho^2/2}$

Signal has a non-central χ^2 distribution
$\Rightarrow$ Gaussian distribution if signal strong enough

31

Ref: http://old.apctp.org/conferences/2011/NRG2011/NRGPDF/CBC_DA_Korean_School_2011.pdf

Network by multiple GW detectors:



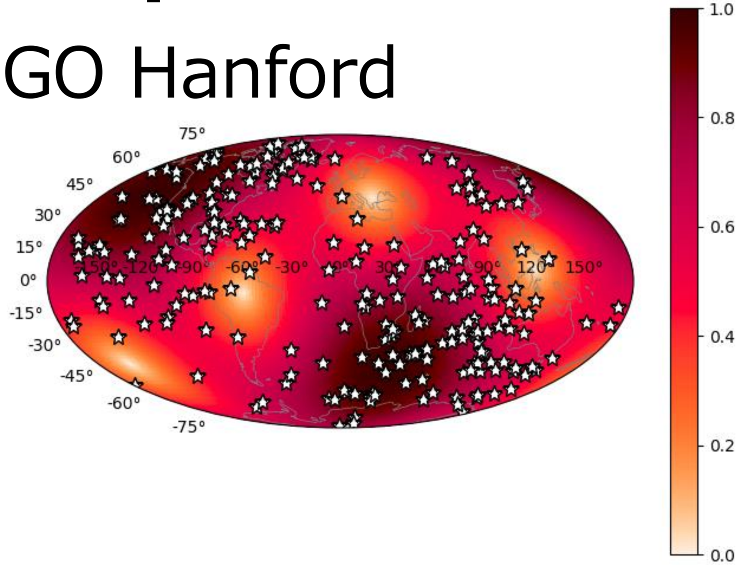
* network duty cycle D_{net}
$\sim$ D1 *D2 *D3 *D4 * …

ex.) Network duty cycle
more than 3 detectors
* if D1 = D2= ⋯ = 80%,

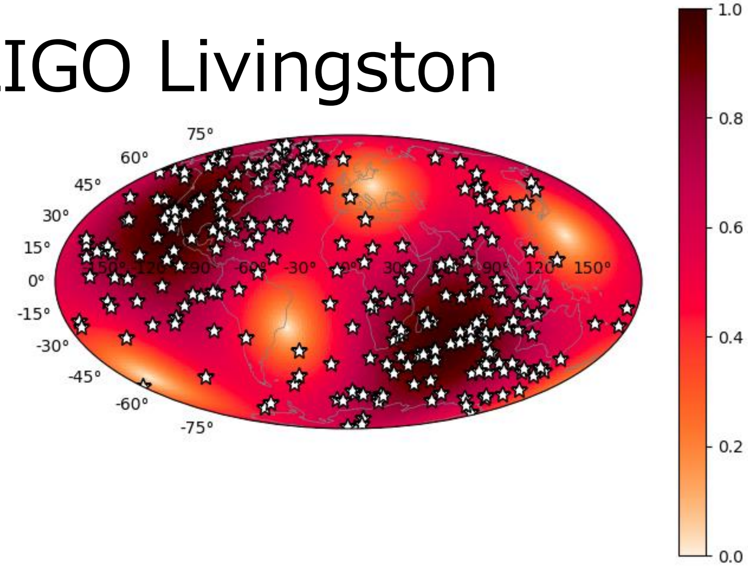
3-detector network: $D_{net} \sim$ 51%
↓ ↓
4-detector network: $D_{net} \sim$ **82%**

Antenna pattern & source position

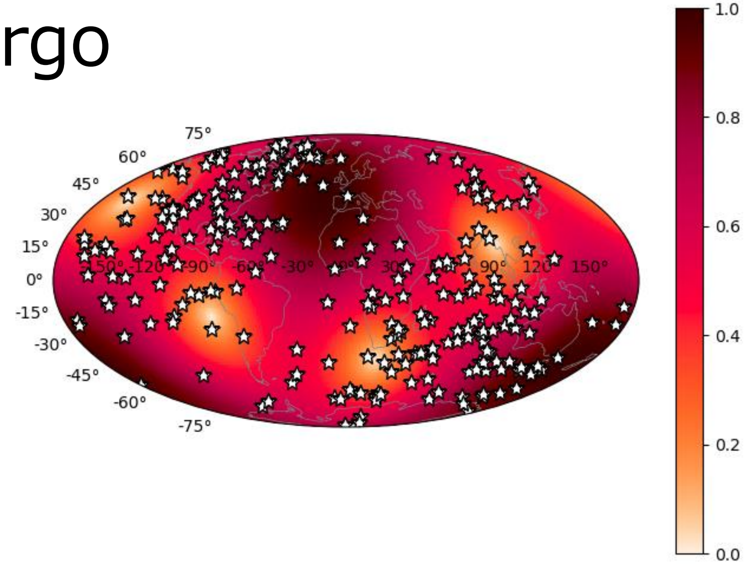
LIGO Hanford



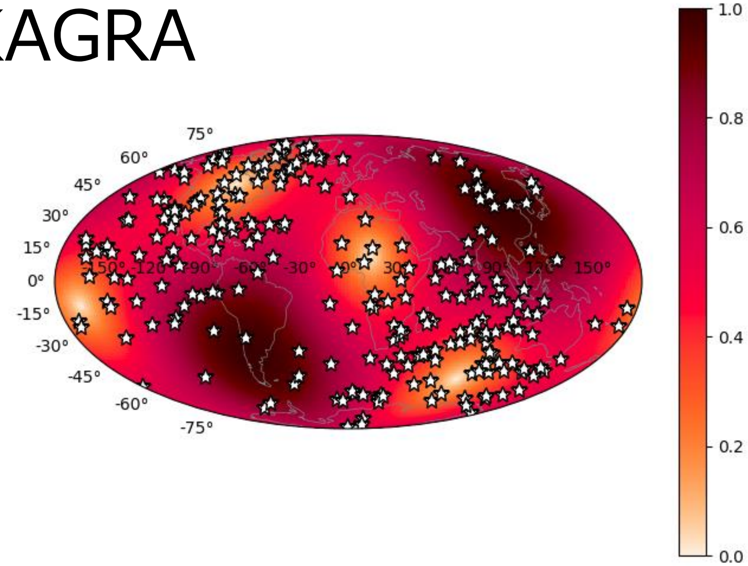
LIGO Livingston



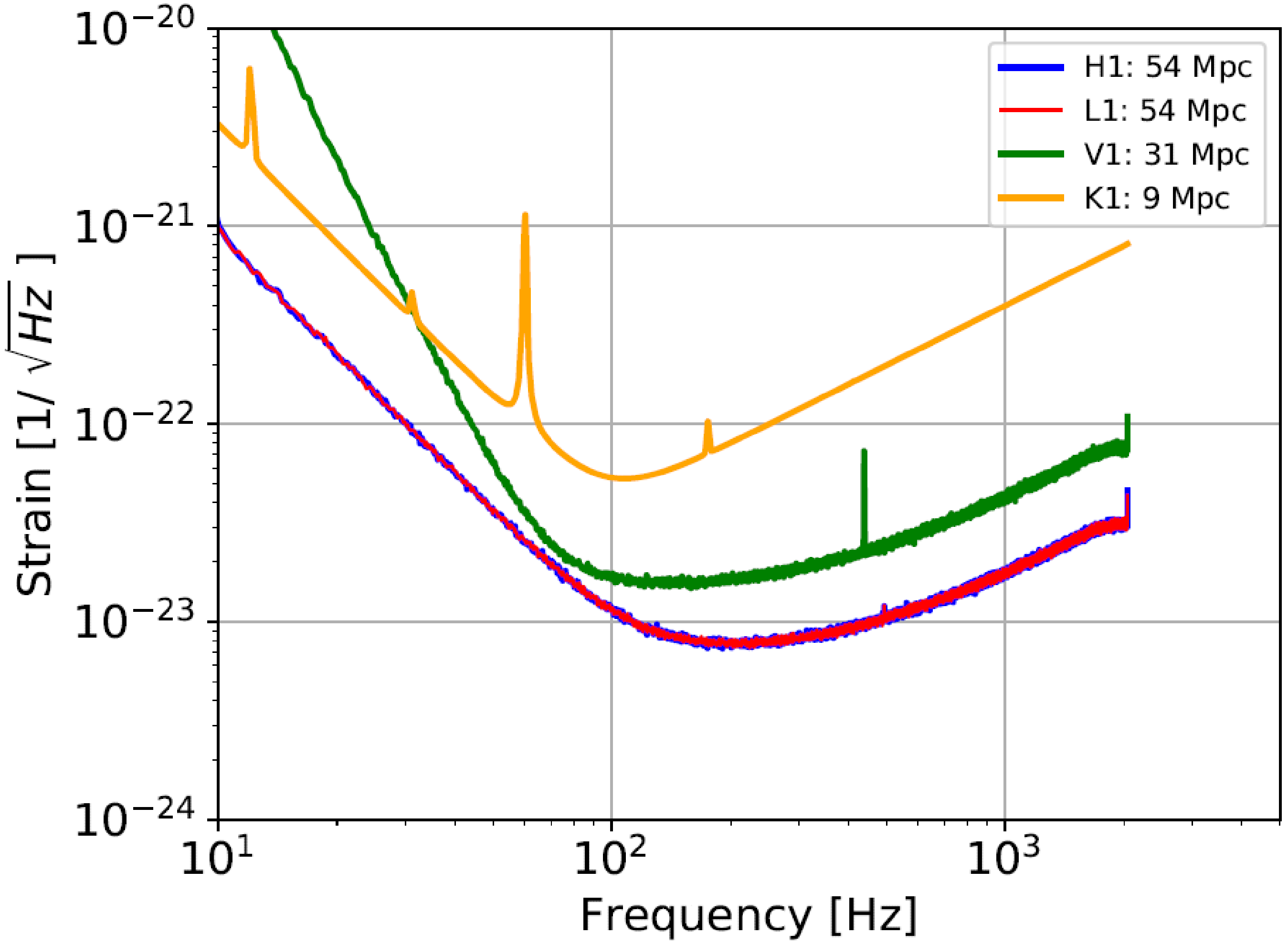
Virgo



KAGRA



Assumed noise curves:



- For V/K,
  the curves are scaled.

Actual threshold in the low-latency analysis in O2:

Table 1. Major parameters of O2 online search pipelines based on compact binary merger waveform models.

	PyCBC Live	GstLAL	MBTAOnline
Total mass	$2M_\odot$ to $500M_\odot$ [a]	$2M_\odot$ to $150M_\odot$ [a]	$2M_\odot$ to $100M_\odot$
Mass ratio	1 to 98	1 to 98	1 to 99
Minimum component mass	$1M_\odot$	$1M_\odot$	$1M_\odot$
Spin magnitude ($m < 2M_\odot$)	0 to 0.05	0 to 0.05	0 to 0.05
Spin magnitude ($m > 2M_\odot$)	0 to 0.998	0 to 0.999	0 to 0.9899
Single-detector SNR threshold for triggering	5.5	4 [b]	5.5 [c]

[a] The maximum total mass for PyCBC Live and GstLAL is in fact a function of mass ratio and component spins (Dal Canton & Harry 2017; Mukherjee et al. 2018) and we indicate the highest total mass limit over all mass ratios and spins. The offline GstLAL search uses a template bank extended to a larger maximum total mass of $400M_\odot$.

[b] This threshold was applied to the two LIGO detectors only for the online GstLAL analysis. The minimum trigger SNR in Virgo was not determined by an explicit threshold, but instead by a restriction to record at most 1 trigger per second in a given template.

[c] MBTAOnline uses a higher LIGO SNR threshold (6) to form coincidences with Virgo.

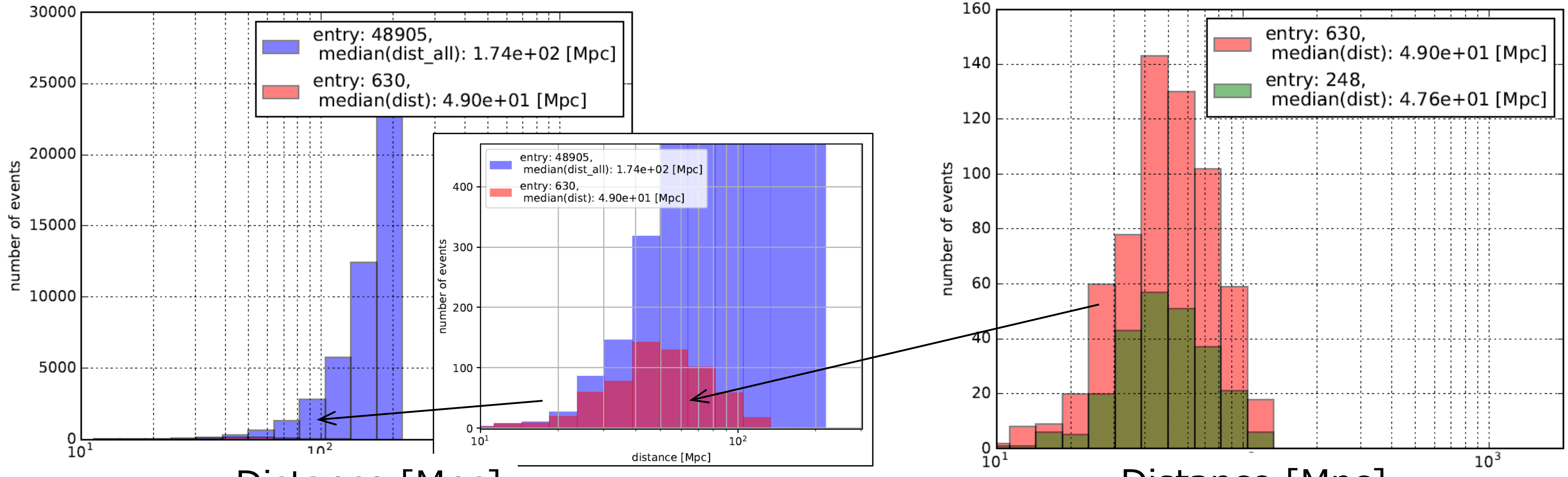
More concretely:

* Component mass: Uniform [1.2 $M_\odot$: 1.6 $M_\odot$]

Injections (number of events: 248)

<u>* Reuse of another calculation [ref] & detected by HL-network:</u>

All injections Random, isotropic (48905 events) → Events detected by HL (630 events) → Randomly selected events (248 events)



Distance [Mpc]

Distance [Mpc]

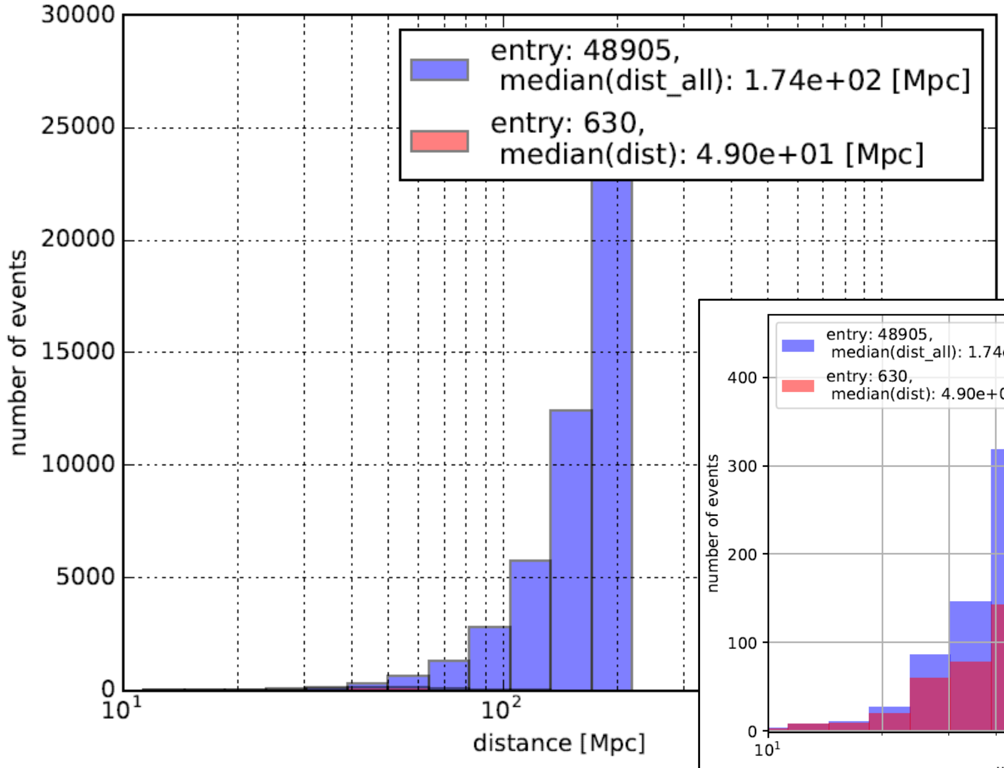
[ref] https://www.ligo.org/scientists/first2years/

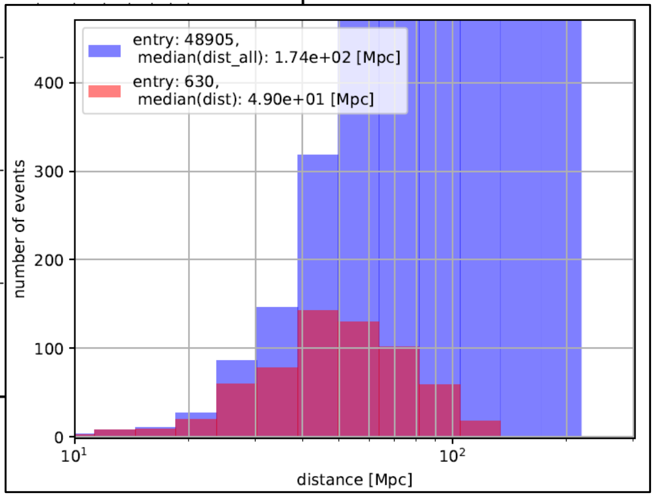
How the inputs obtained?: 2015 scenario in [1] vs. 2016sim

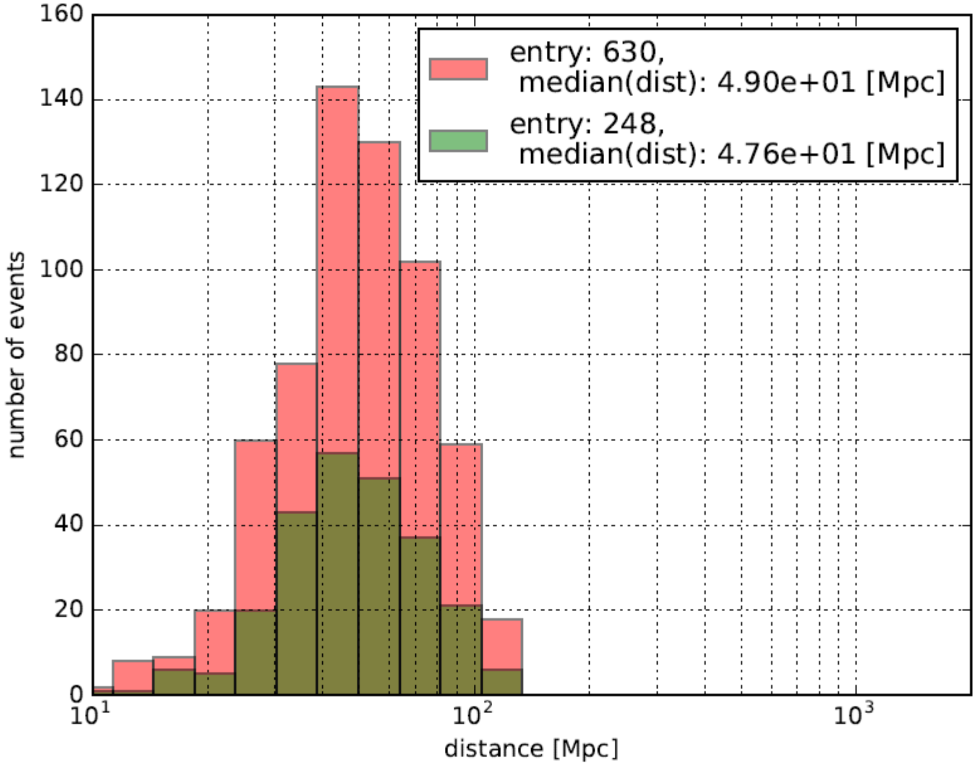
* Configuration (number of events)
* Component mass: Uniform [1.2 $M_\odot$: 1.6 $M_\odot$]
* All injections (48905) ⟶ * Found events (630) ⟶ * Used in simulation (248)

Randomly selected in order to save computational cost.

2 events missed





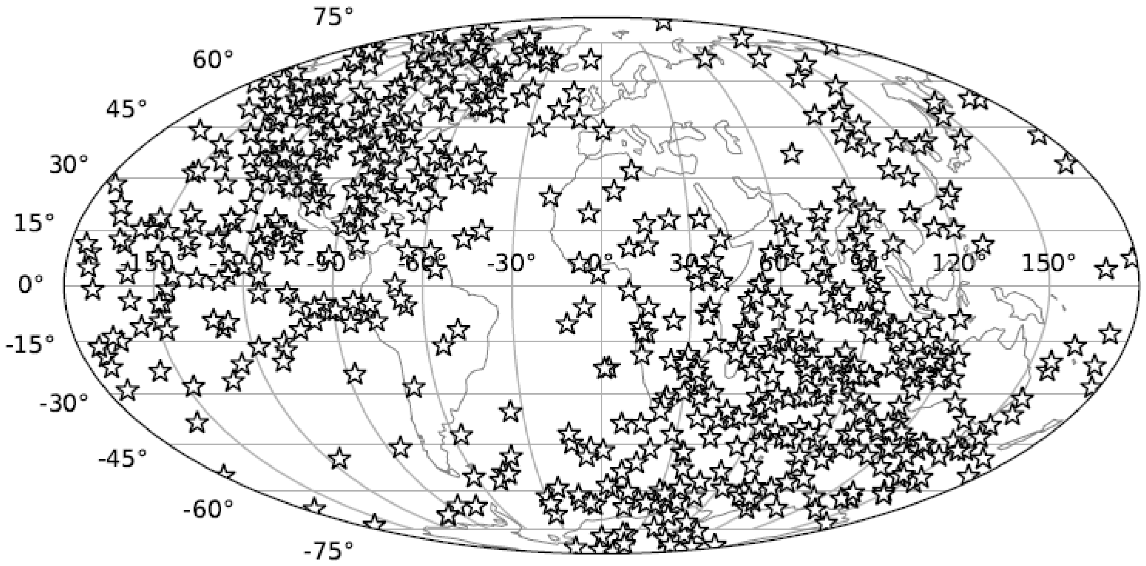


[1] https://www.ligo.org/scientists/first2years/

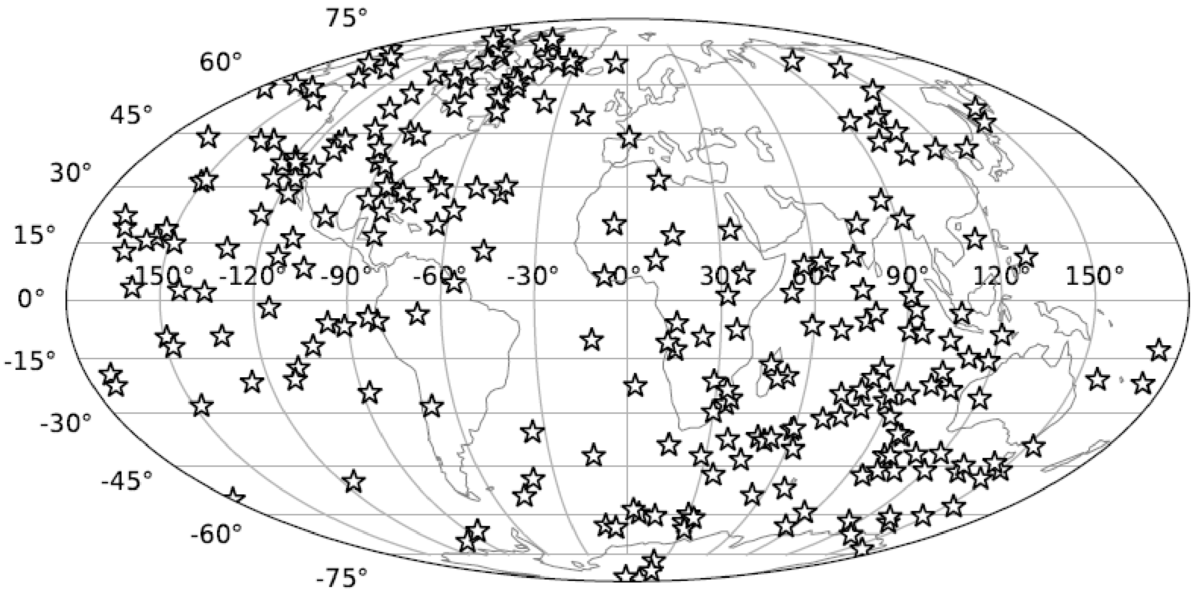
How the inputs obtained?:

In 2015 scenario in [1]

* Found events (630)



* Used events (248)



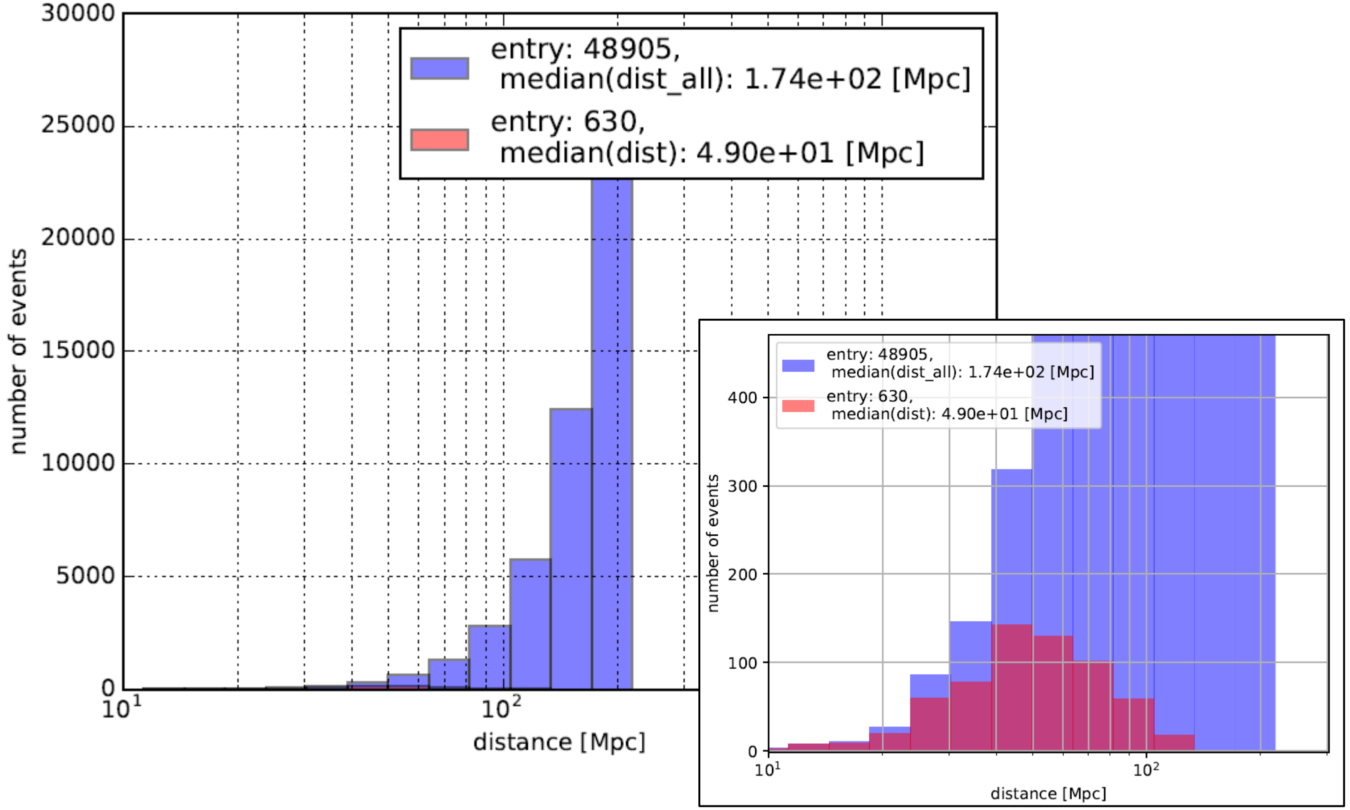
Reference: the inputs:

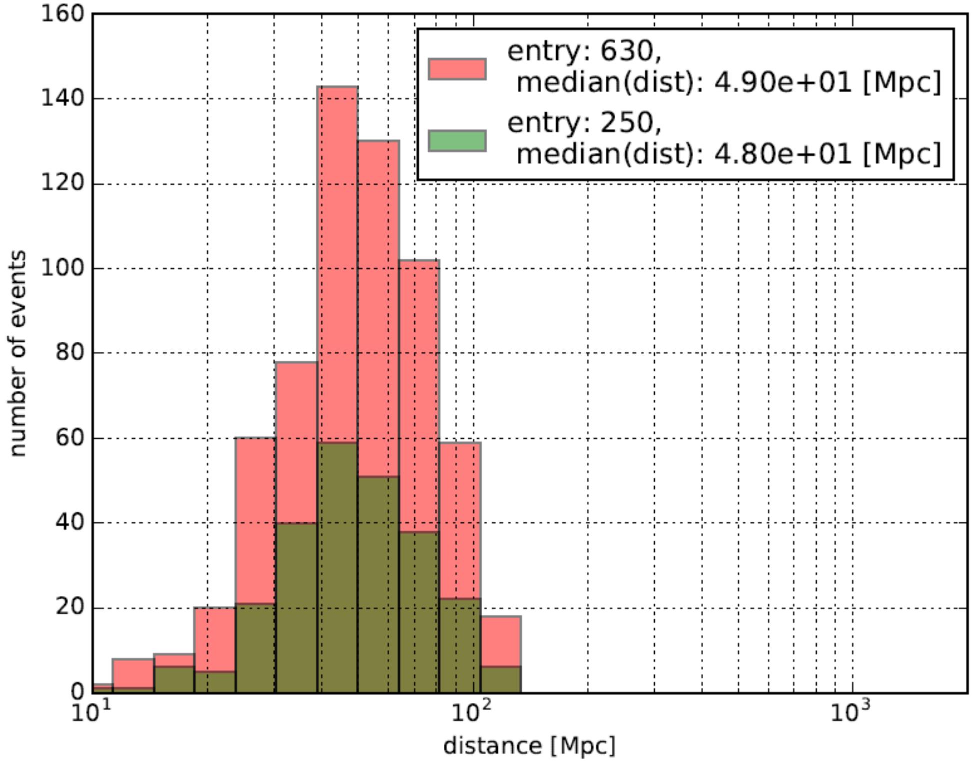
In 2015 scenario in [1]

* Configuration (number of events)
* Component mass: Uniform [1.2 M⊙ : 1.6 M⊙]

Randomly selected in order to save computational cost.

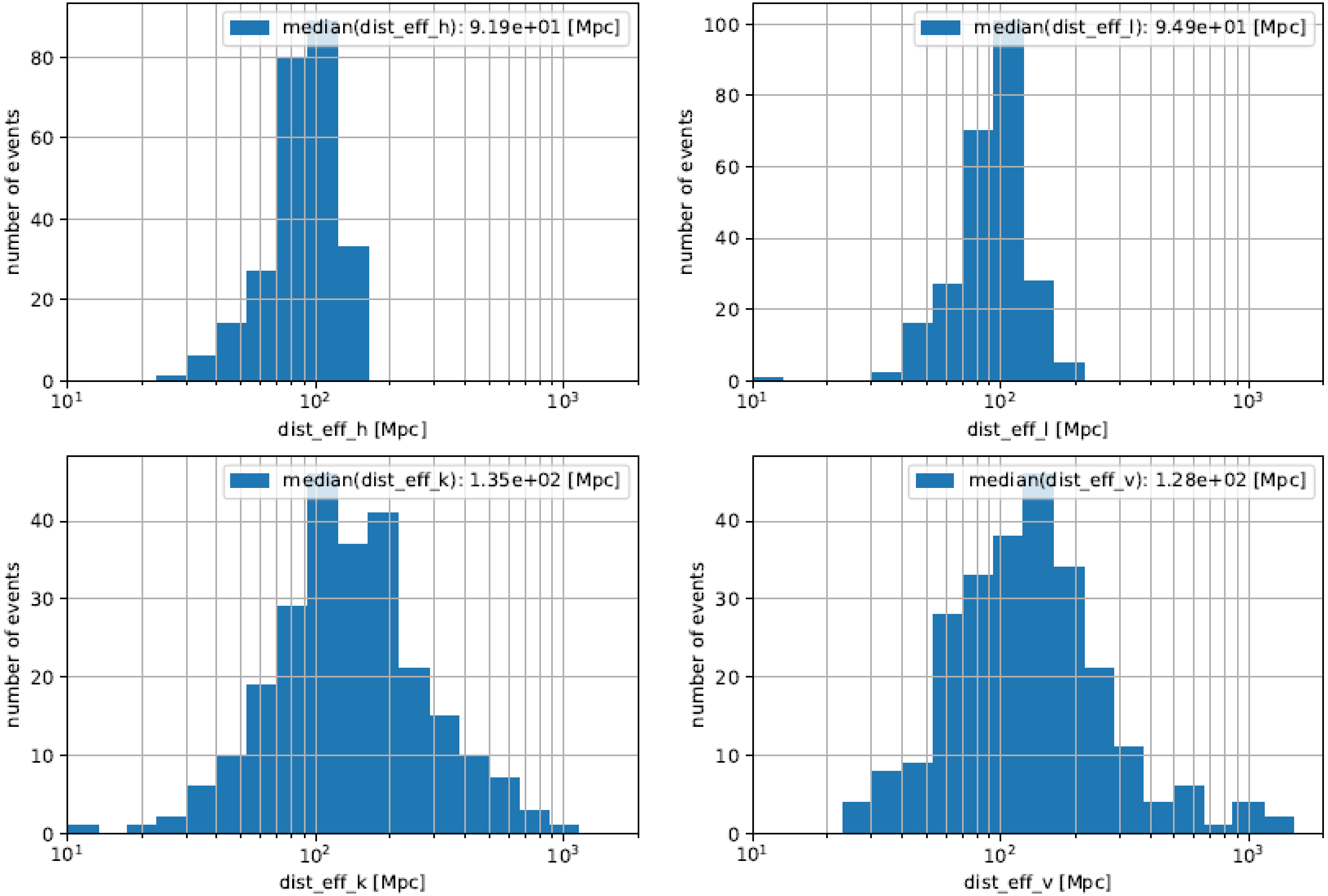
* All injections (48905) ⟶ * Found events (630) ⟶ * Used in simulation (250)





[1] https://www.ligo.org/scientists/first2years/

Effective distances of the injections:



Expected SNR, ρ:

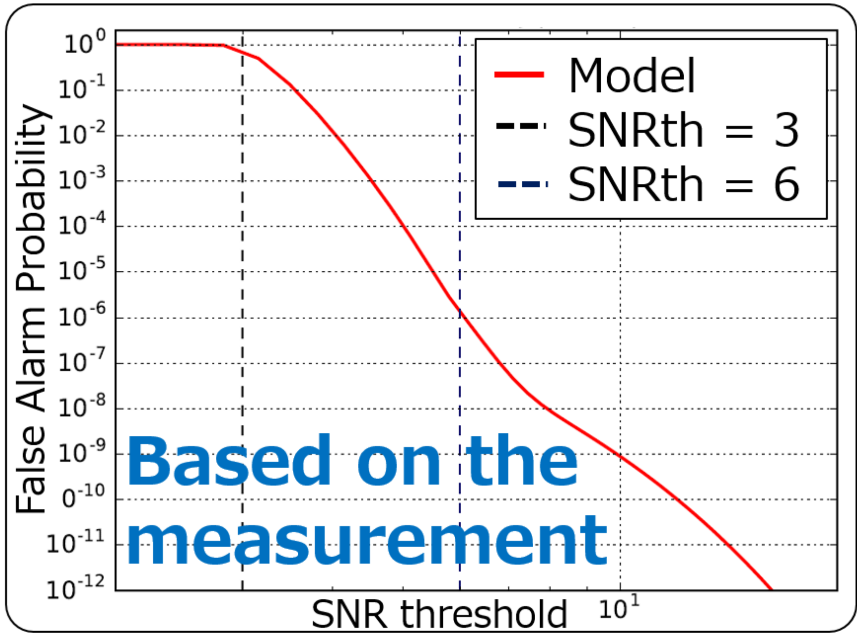
$$\rho = \frac{8 * 2.26 * R\_det}{D\_eff}$$

Generating & mixing artificial V triggers

2. Mixing HLV triggers

p = random [0:1]
FAP = *FAP*(*SNR*) or *FAP*(SNRth)

p<*FAP* → HLV*r*
p>*FAP* & *SNR*>SNRth → HLV*i*
p>*FAP* & *SNR*<SNRth → HL



noise. (*Right*) False alarm probability (FAP) as a function of the SNR threshold, computed as $\text{FAP} = 1 - \exp(-R\,T)$, with R the rate of triggers above threshold per template, derived from the distribution on the left, and $T = 70$ ms. At low

Table 2.1: Procedure for generating coincident events for LIGO-Virgo network. p_V is a random number from a uniform distribution between 0 and 1. FAP_V is the false alarm probability at a given SNR threshold in Virgo.

Conditions	Generated coincidences
if $p_V < \text{FAP}_V(\,max(SNR_V^{th},\ SNR_V^{expected})\,)$	H L V_n
else	
if $SNR_V^{expected} > SNR_V^{th}$	H L V_i
if $SNR_V^{expected} < SNR_V^{th}$	H L

Generating & mixing artificial V triggers

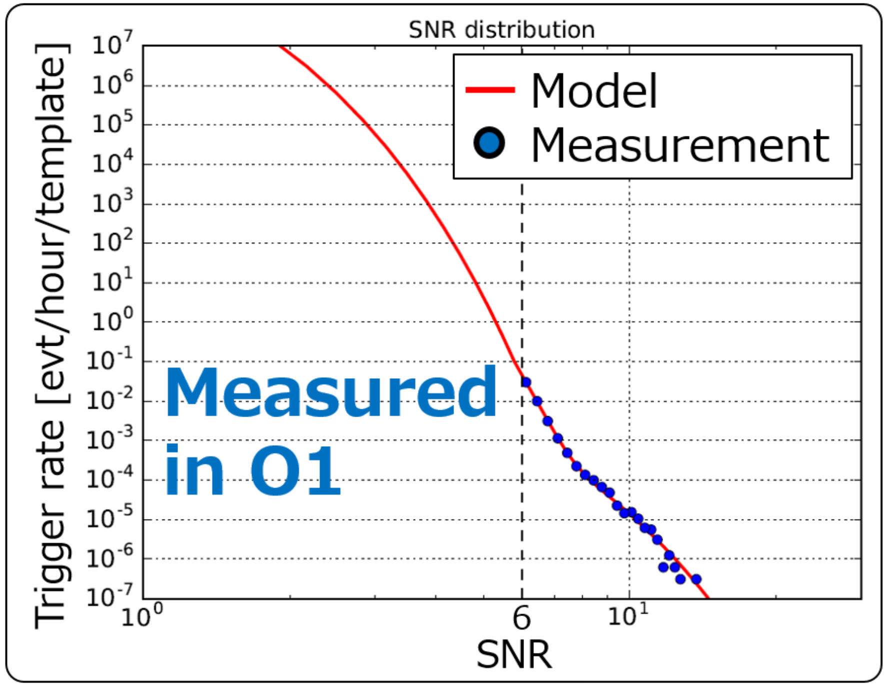
1. Generating V triggers

V_r : V trigger based on random parameters

SNR = random following measurement ←

Time = t_{H1} or t_{L1} + random [-35ms:35ms]

Phase = random $[0:2\pi]$



V_i : V trigger based on injection parameters

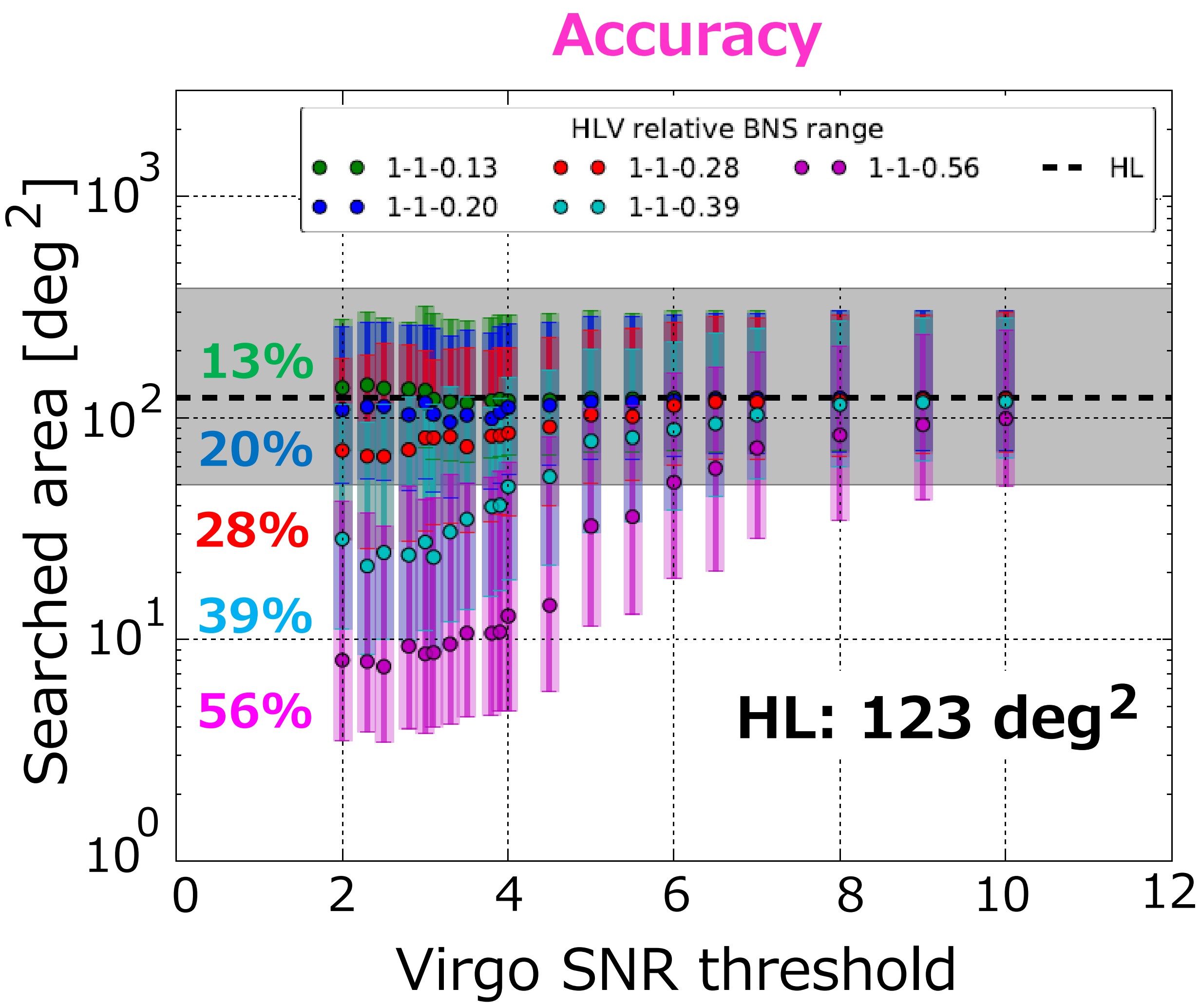
SNR = metadata + Gauss(0,1)

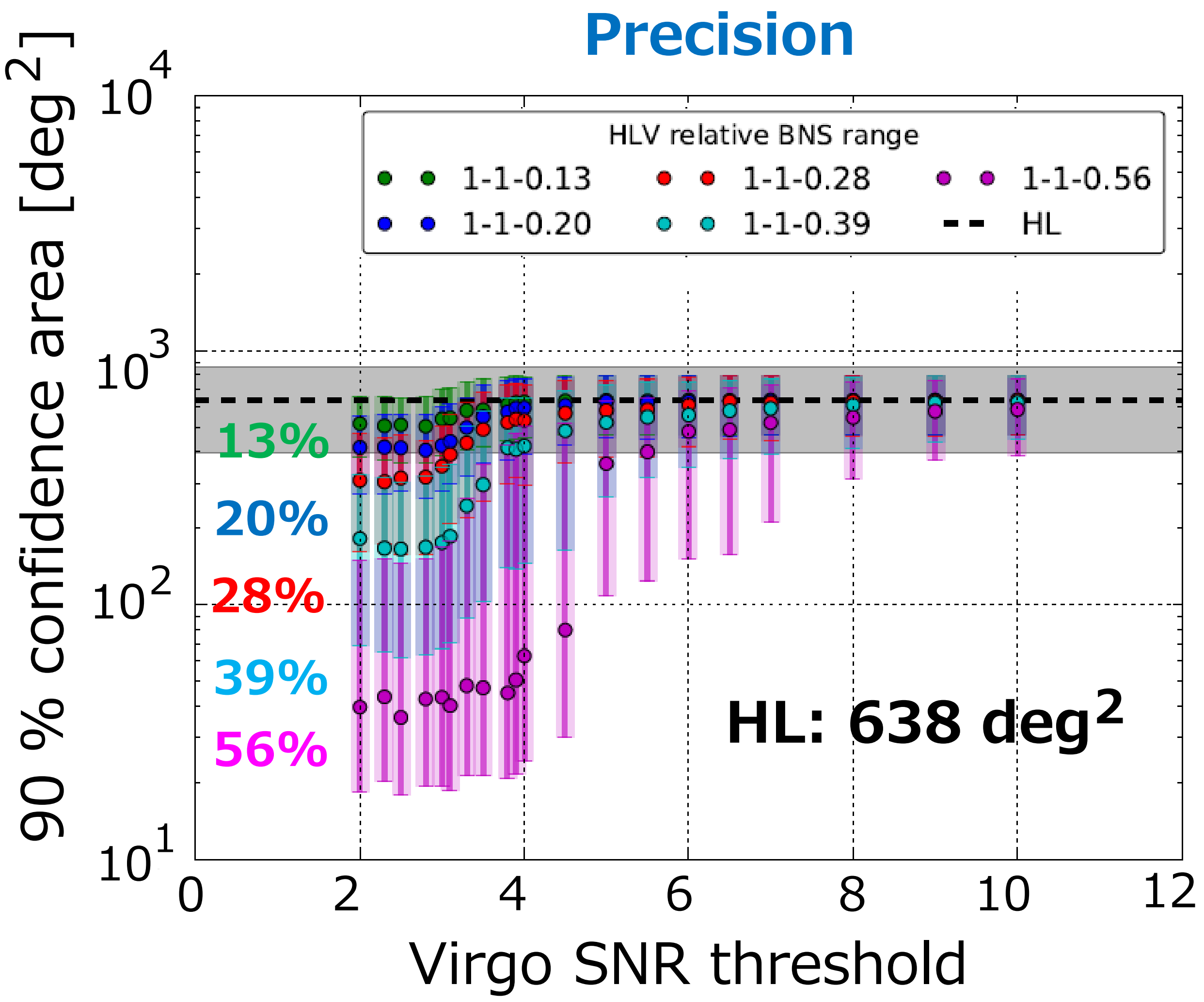
Time = metadata + Gauss$(0, 0.66\ \mathrm{ms} * \frac{6}{\mathrm{SNR}})$

Phase = metadata + Gauss(0,0.25 rad)

Performance (HLV):

(SNR threshold for H, L = 5.)

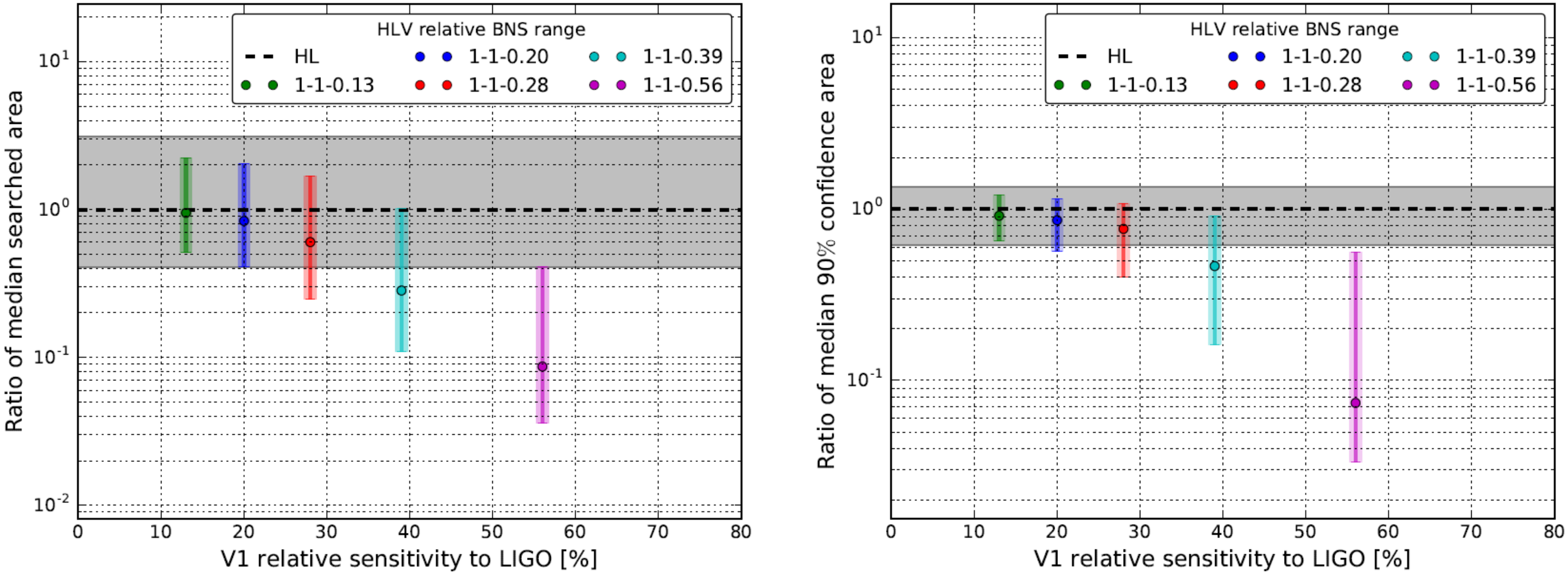




Performance of HL- vs. HLV-hierarchical-network:

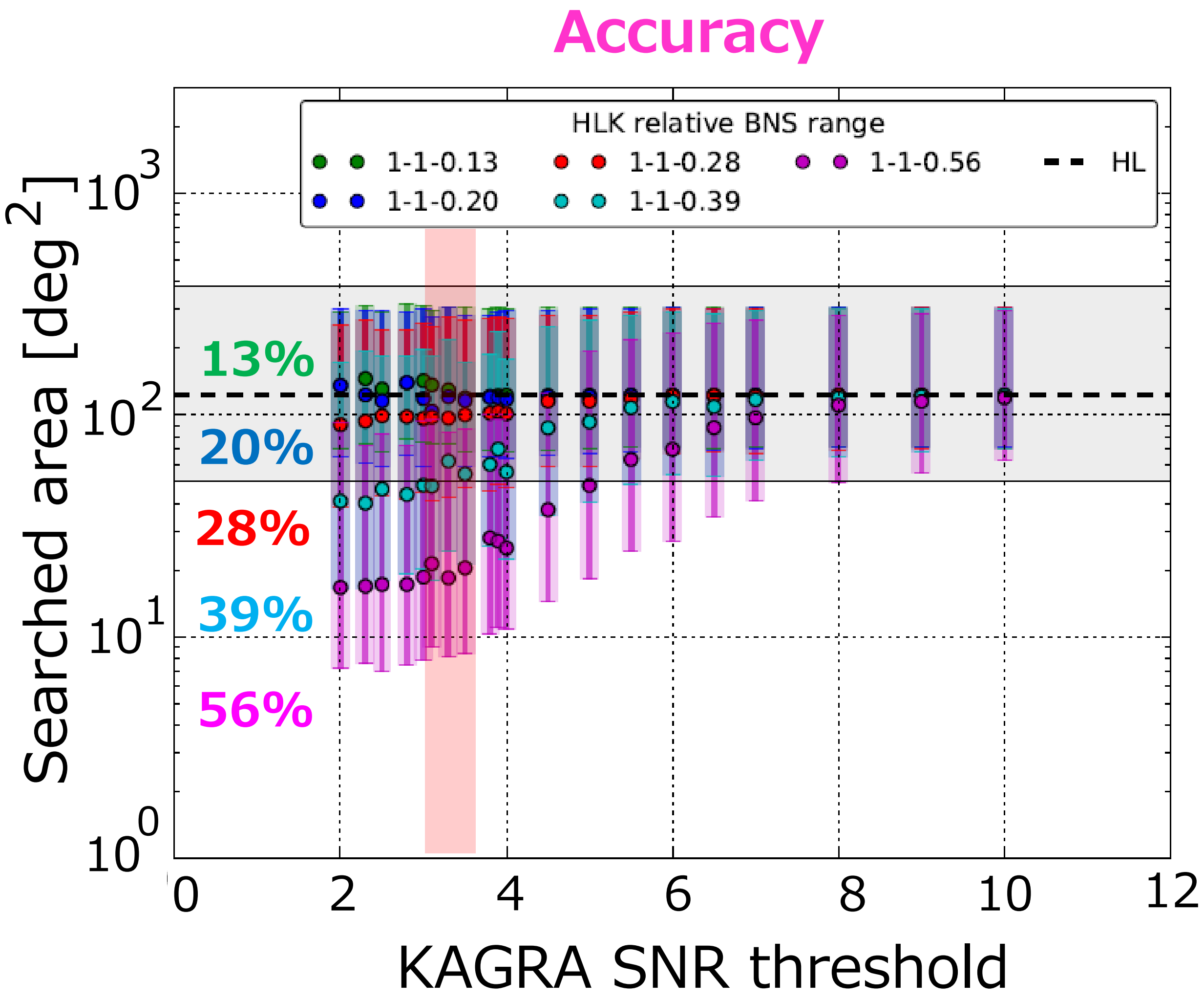
RnageH : RangeL = 54 : 54 (Mpc)

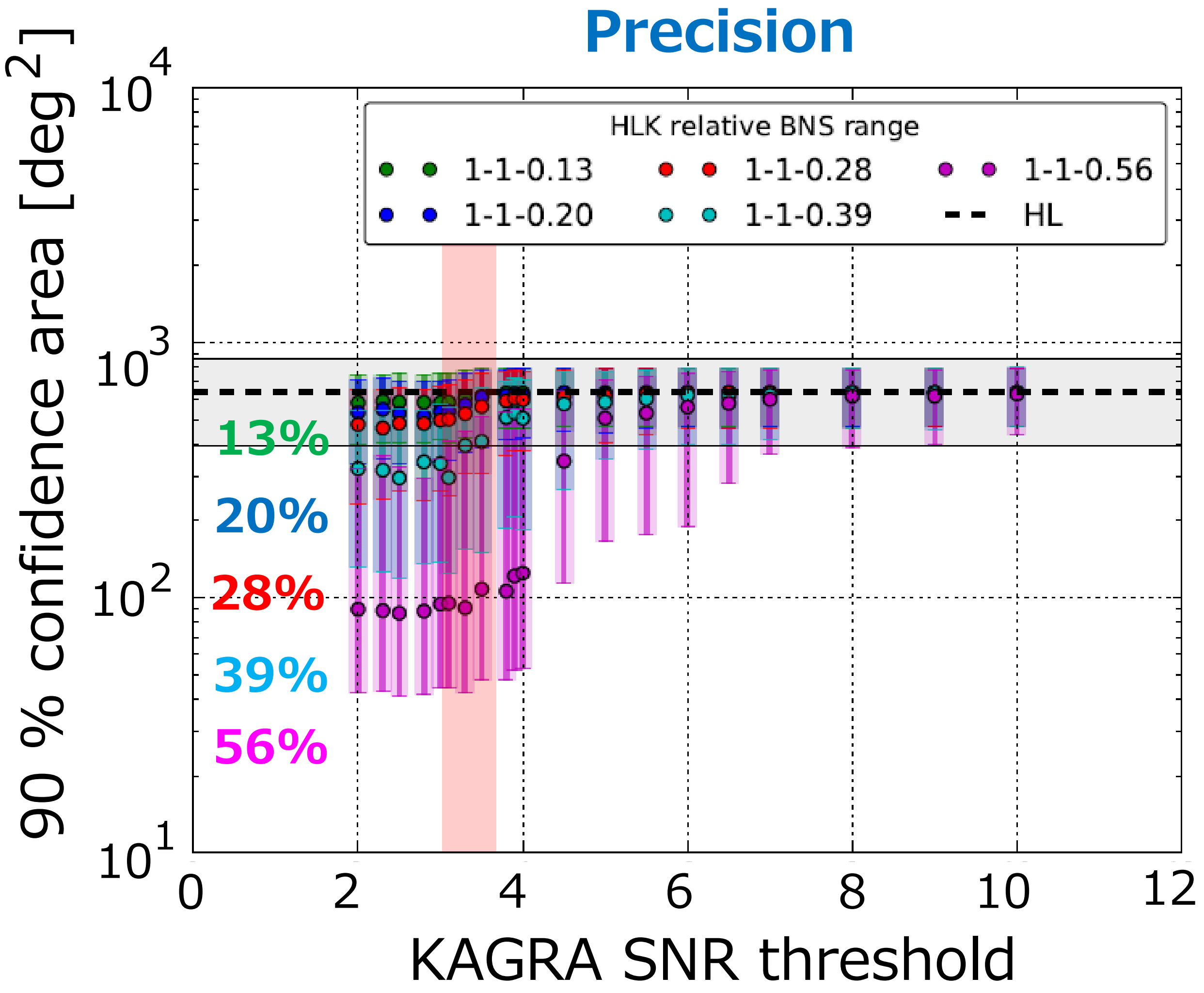
H1th : L1th : V1th = 5 : 5 : 3.5



Performance (HLK):

(SNR threshold for H, L = 5.)



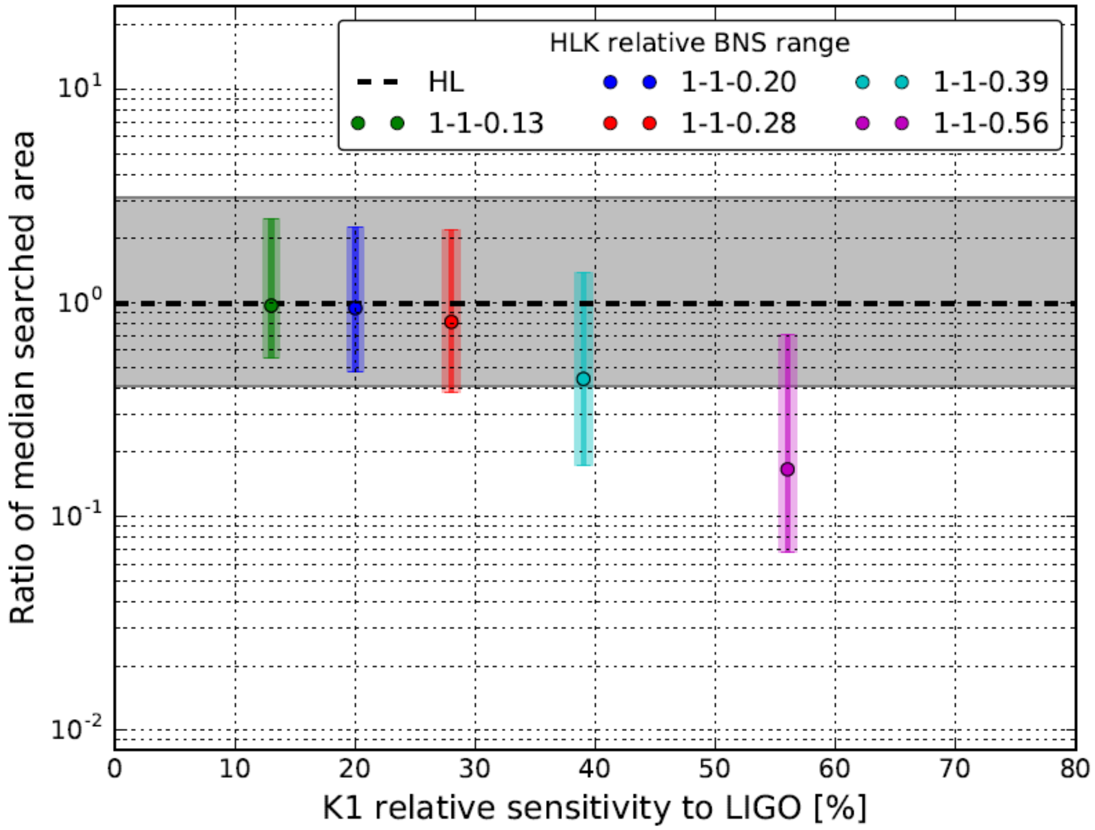


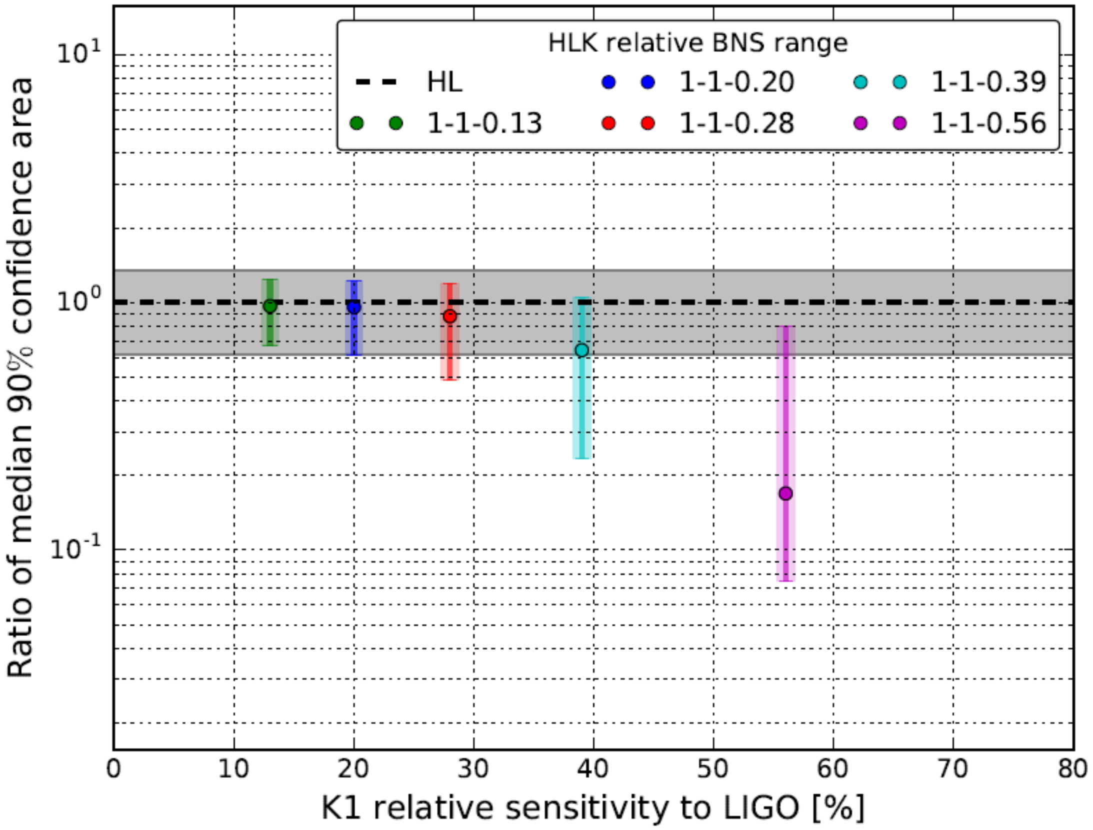
Relative sensitivity = (1, 1, >0.28), SNR threshold = (5, 5, ~3.5)
→ **becomes improved**

Performance of HL- vs. HLK-hierarchical-network:

RnageH : RangeL = 54 : 54 (Mpc)

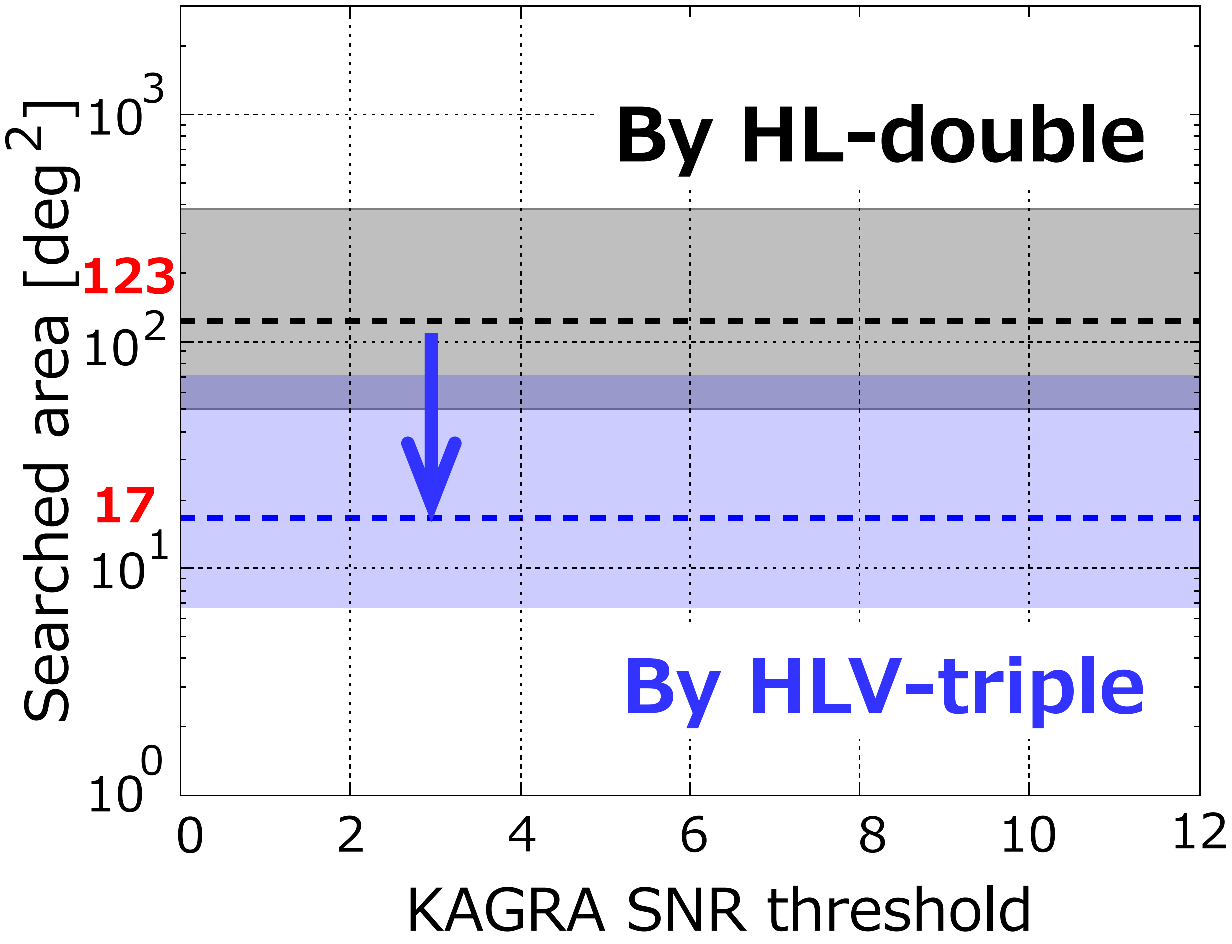
H1th : L1th : K1th = 5 : 5 : 3.5



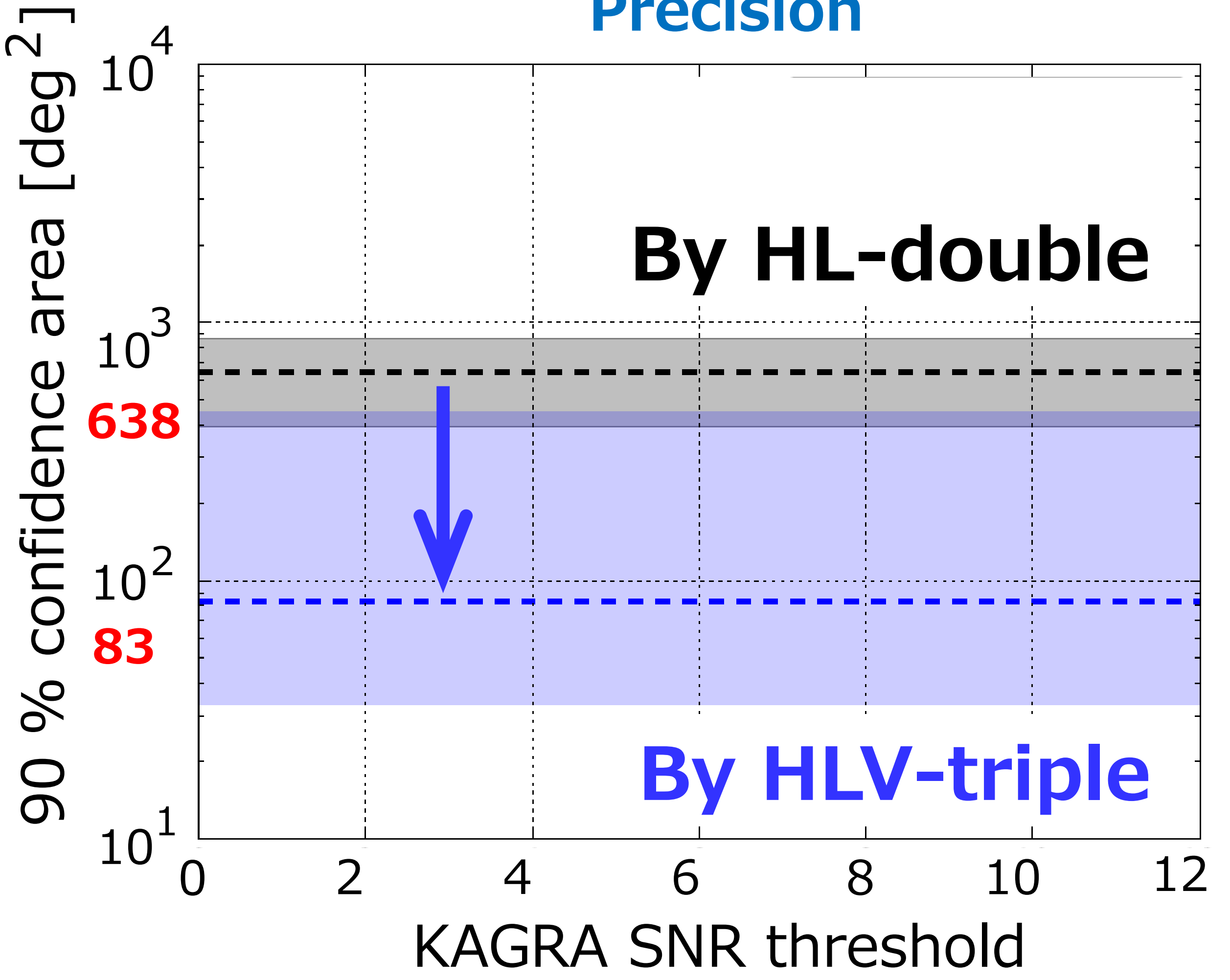


Performance (HL vs. HLV): **(SNR threshold for H, L, V = 5, 5, 3.5)**

Accuracy

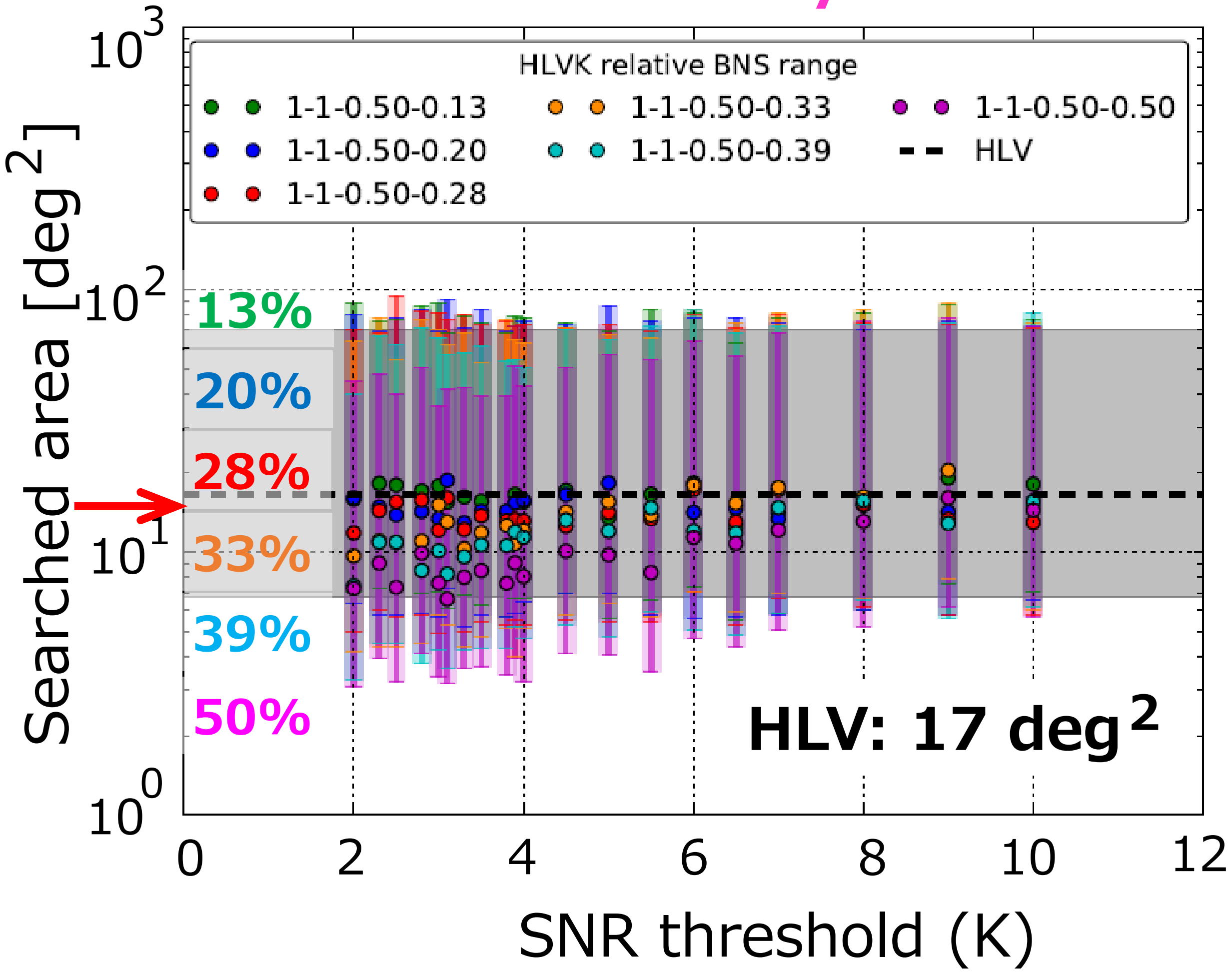


Precision

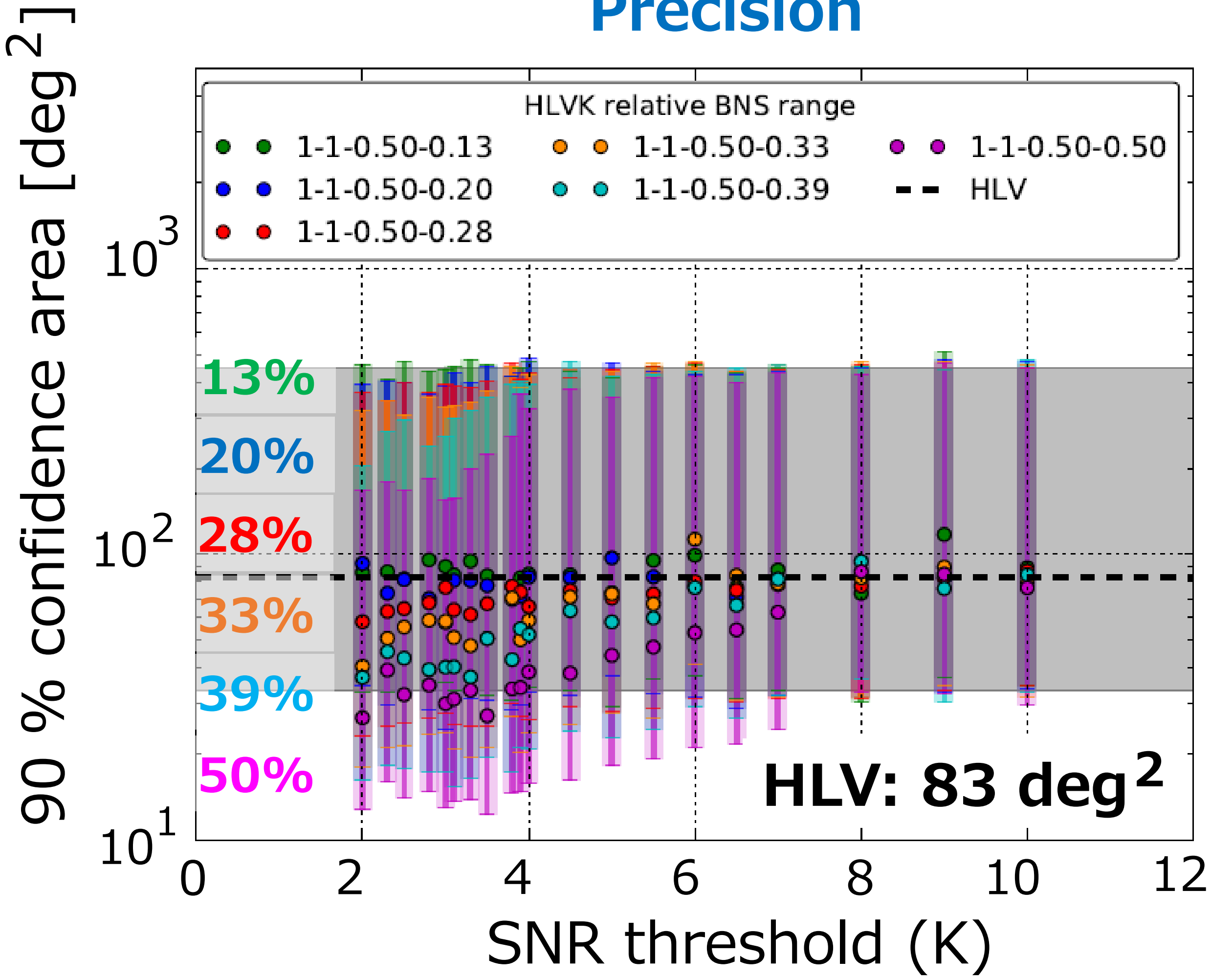


Performance (HLVK): (SNR threshold for H, L, V = 5, 5, 3.5)

Accuracy



Precision

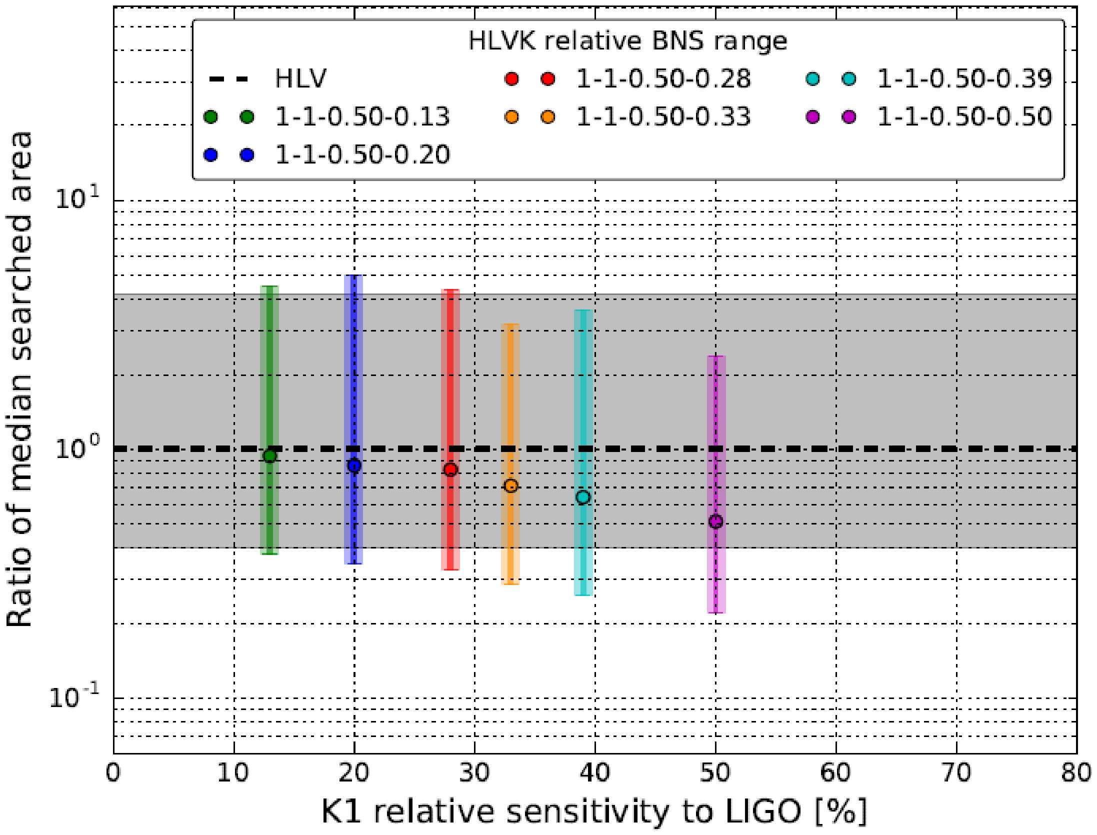


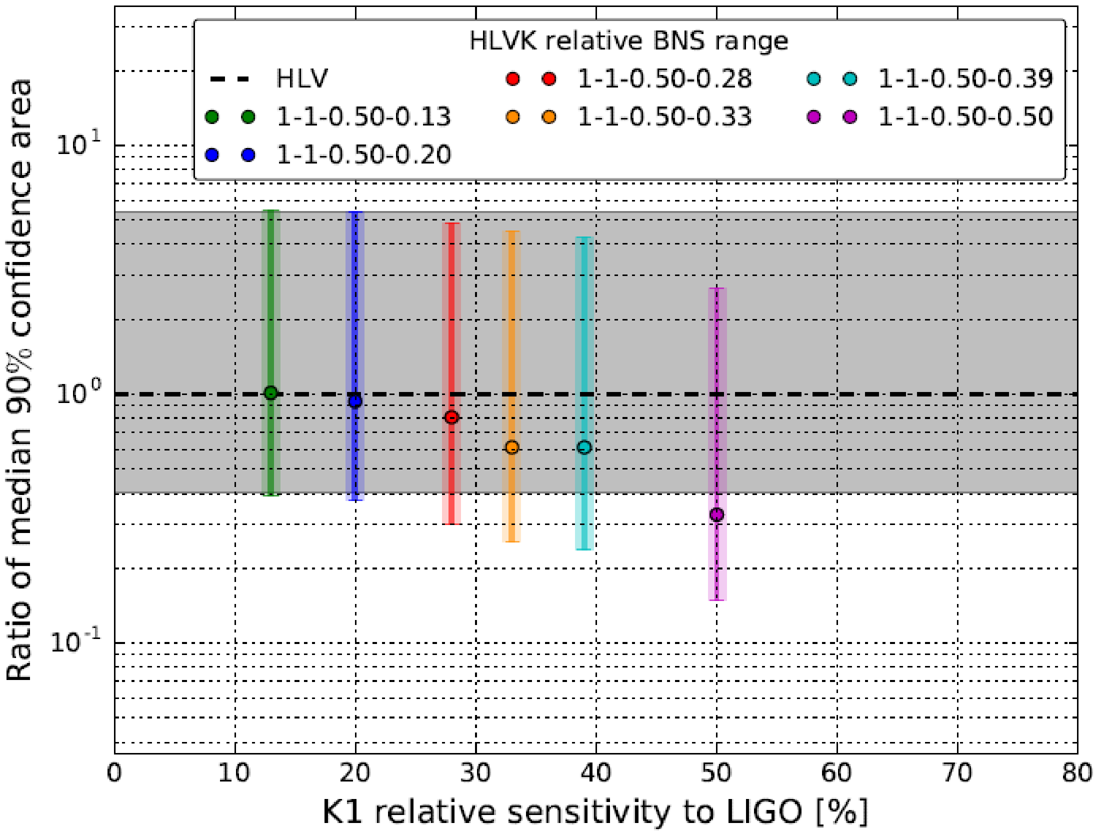
Relative sensitivity = (1, 1, >0.3), SNR threshold = (5, 5, ~3.5)
→ **Effectively improved**

Performance of HL- vs. HLK-hierarchical-network:

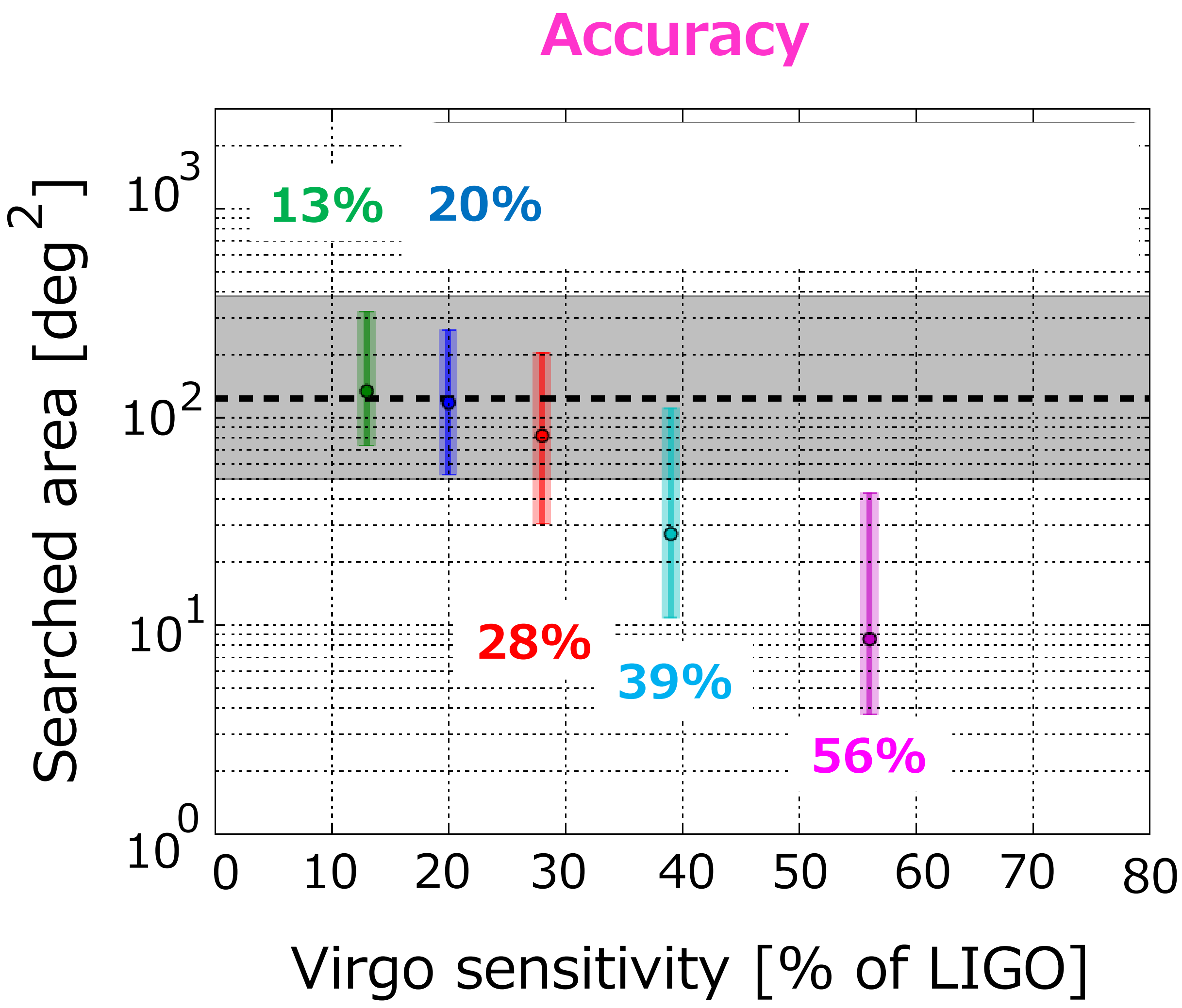
RnageH : RangeL : RangeV = 54 : 54 : 27 (Mpc)

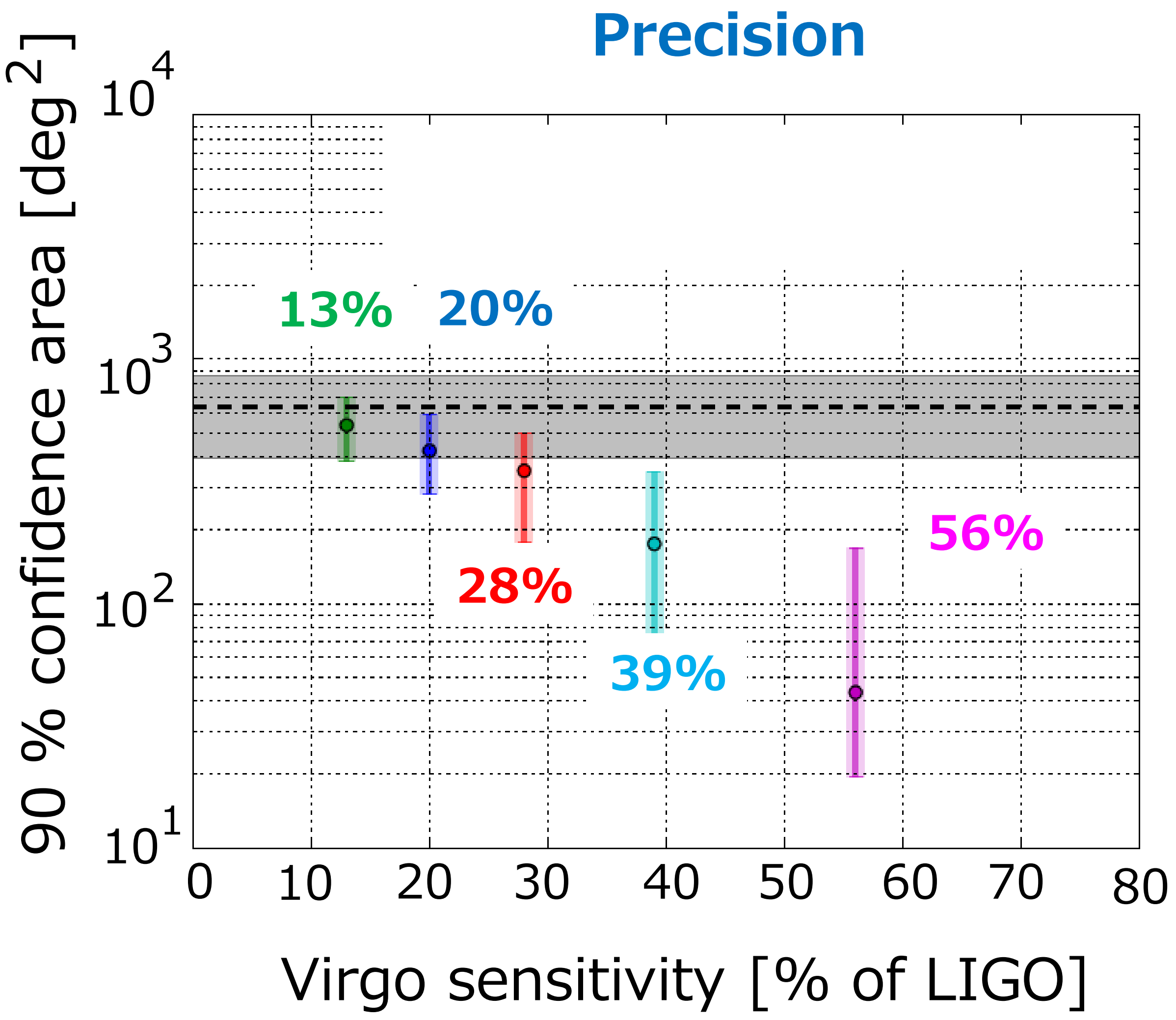
H1th : L1th : V1th : K1th = 5 : 5 : 3.5 : 3.5





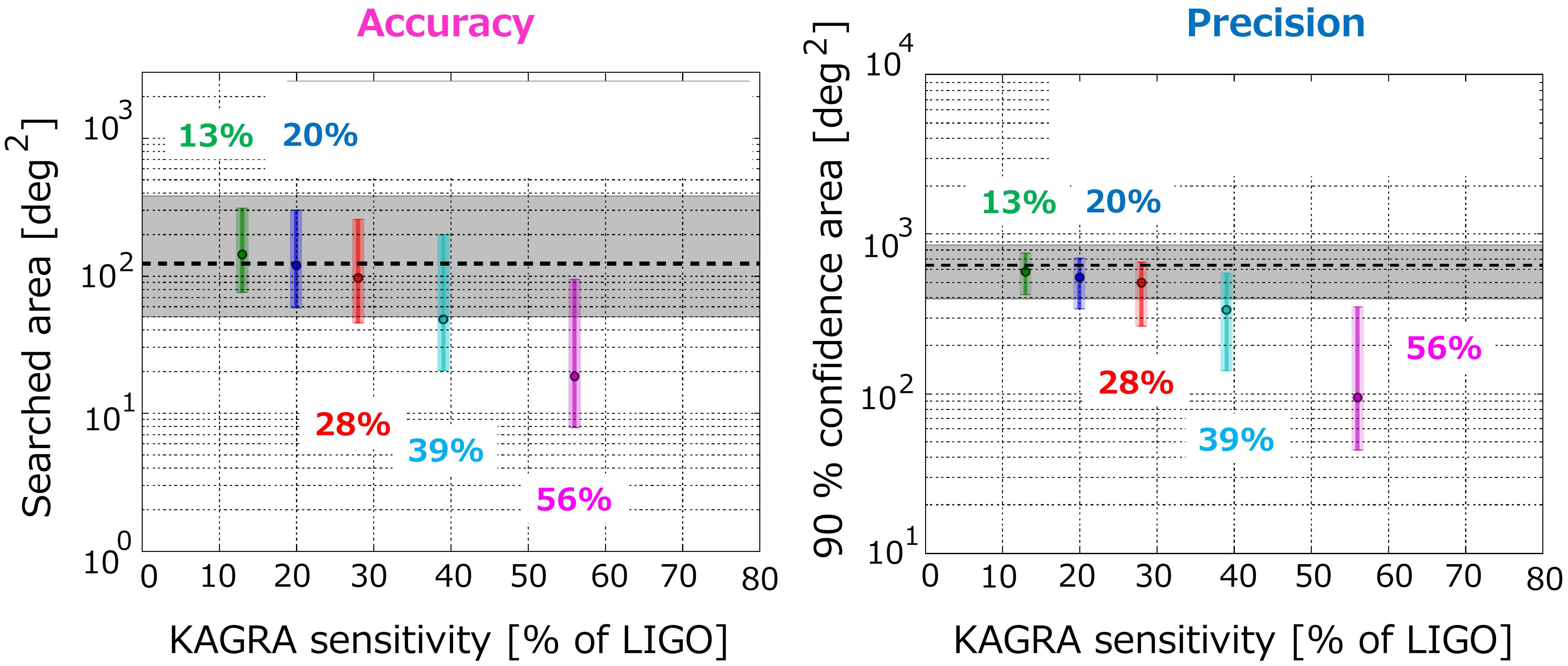
Performance (HLV): (SNR threshold for H, L, V = 5, 5, 3.0)





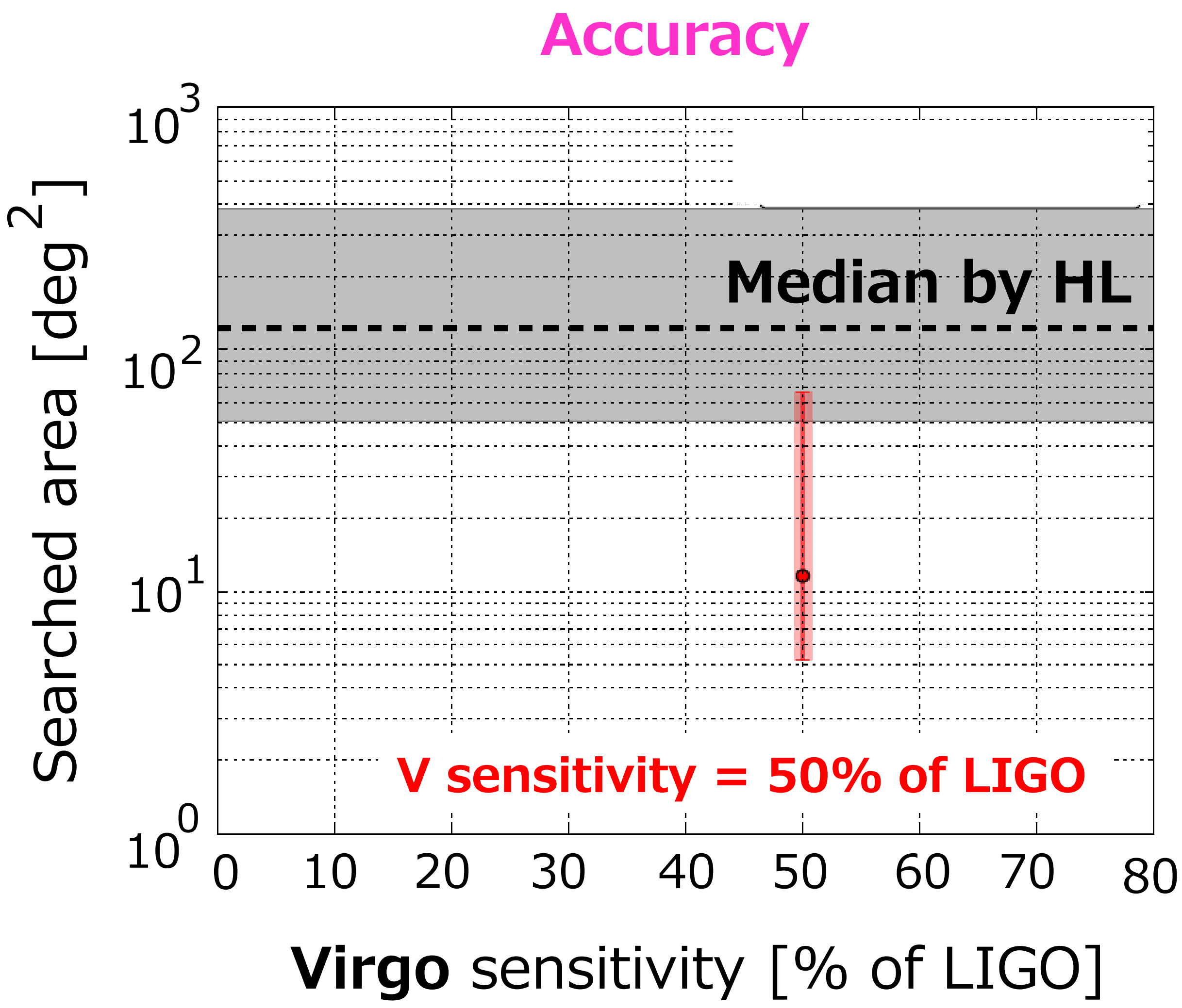
Required: Virgo sensitivity > 20% of LIGO

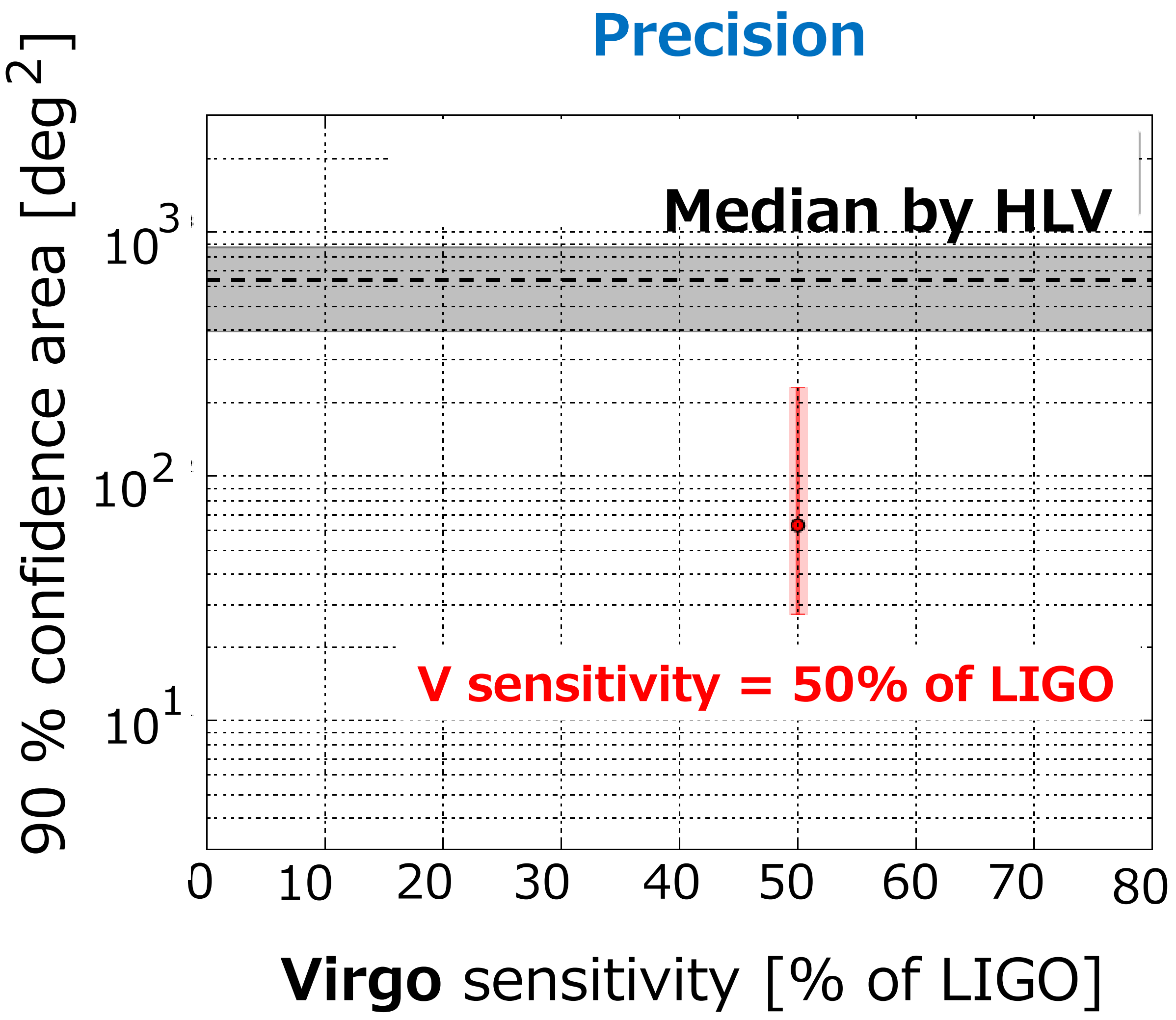
Performance (HLK): (SNR threshold for H, L, K = 5, 5, 3.0)



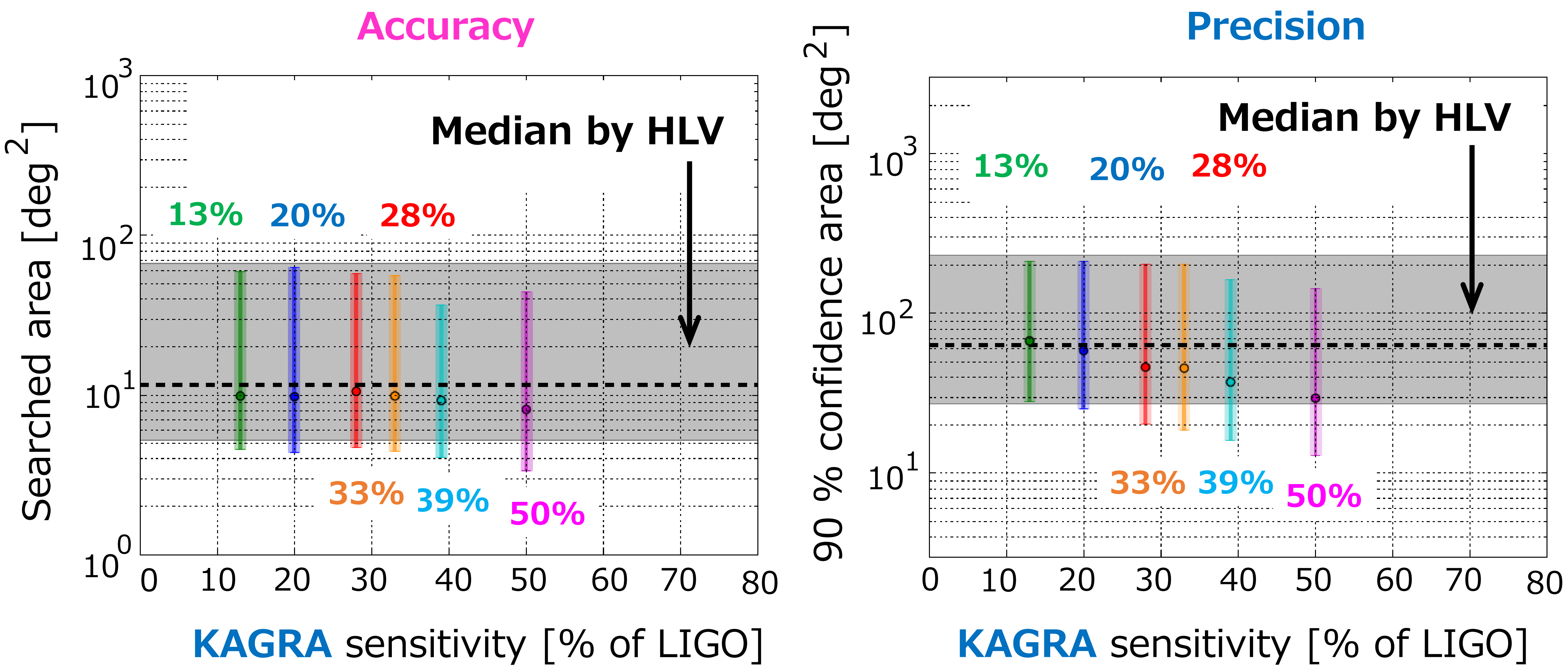
Required: KAGRA sensitivity > 28% of LIGO

Performance (HLV): (SNR threshold for H, L, V = 5, 5, 3.0)



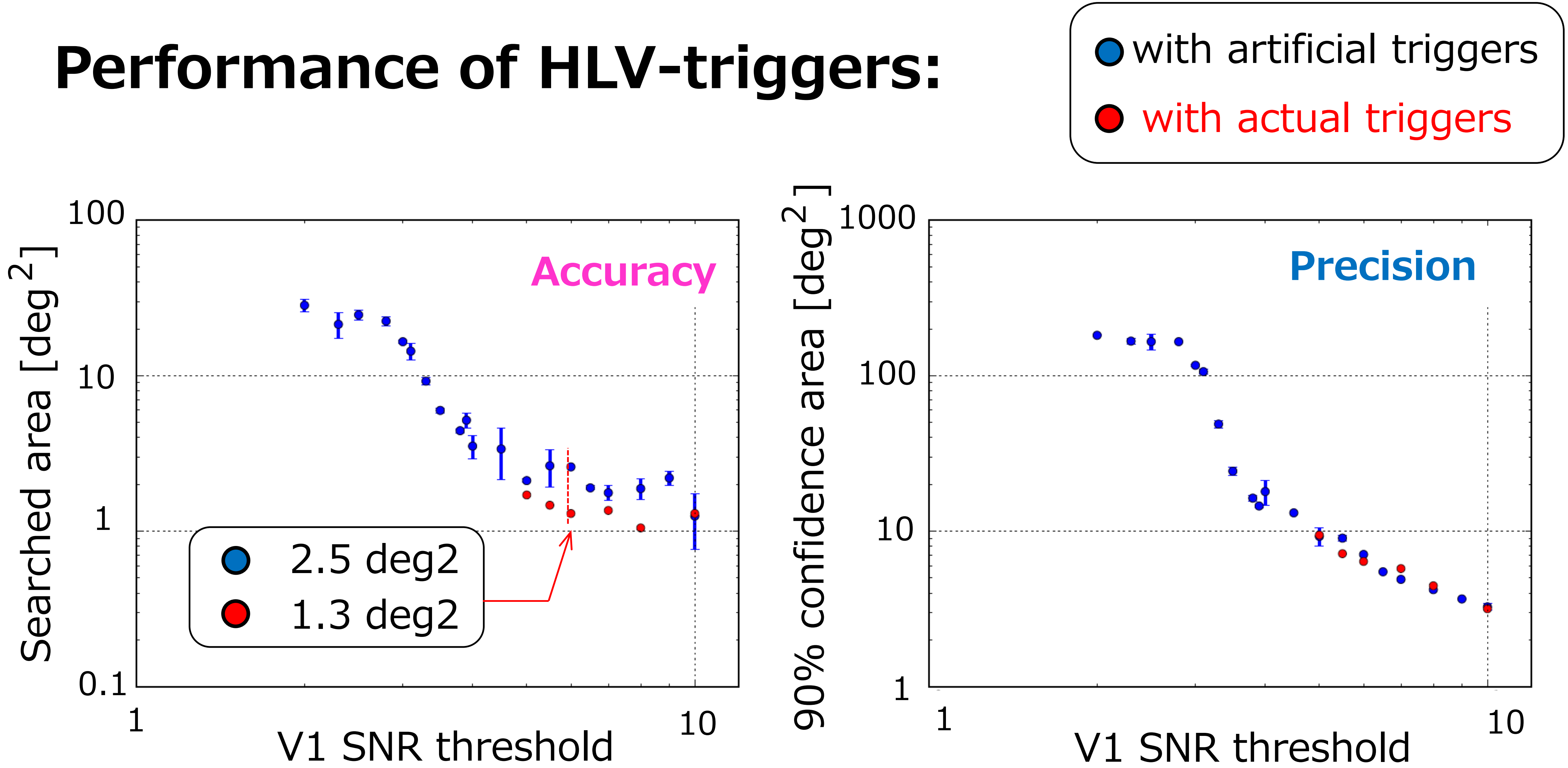


Performance (HLVK): (SNR threshold for H, L, V, K = 5, 5, 3.0, 3.0)



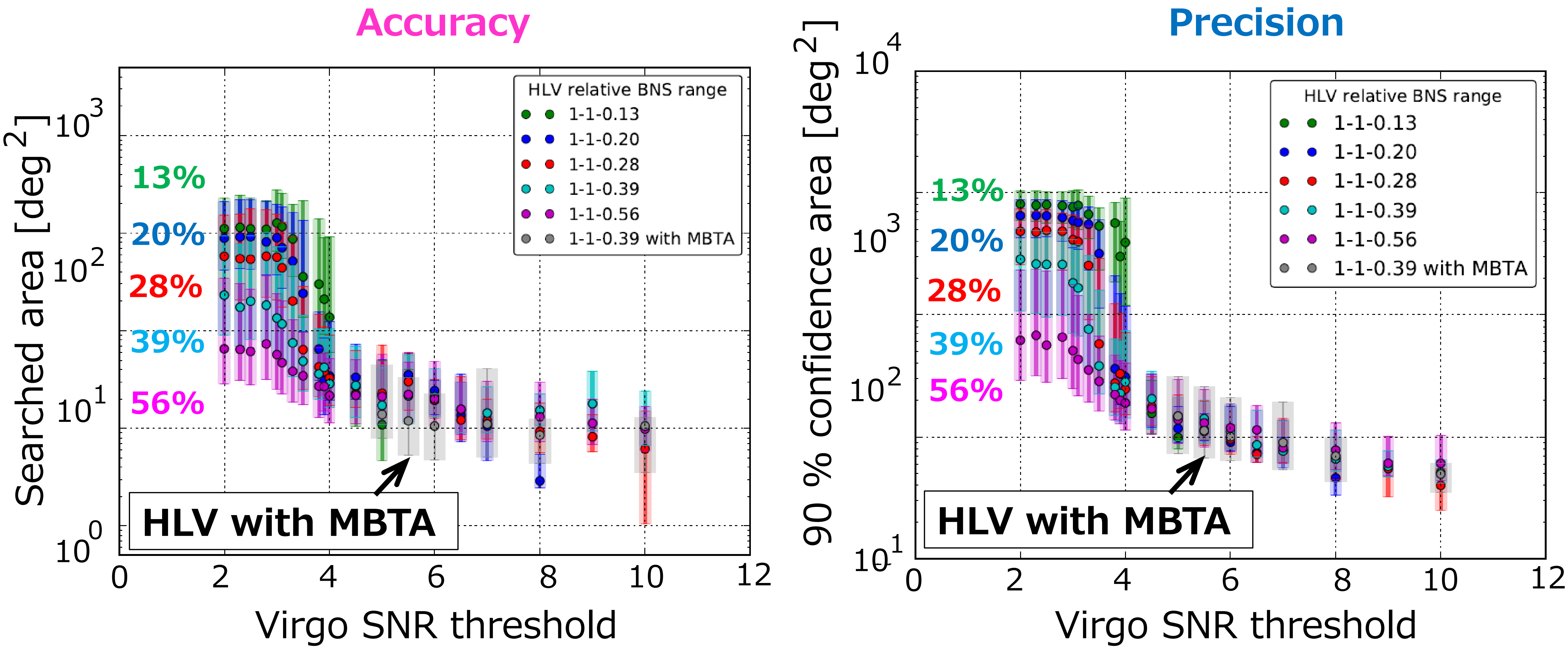
Required: KAGRA sensitivity > 28% of LIGO

Performance of HLV-triggers:



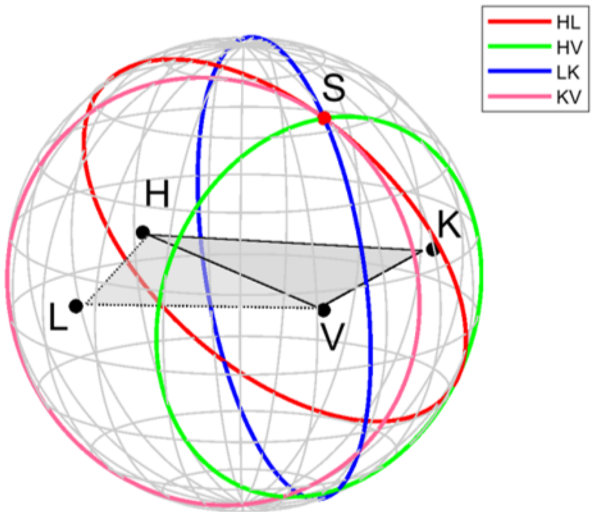
Simulation vs. running MBTA → consistent

Performance (HLV): (SNR threshold for H, L = 5.)

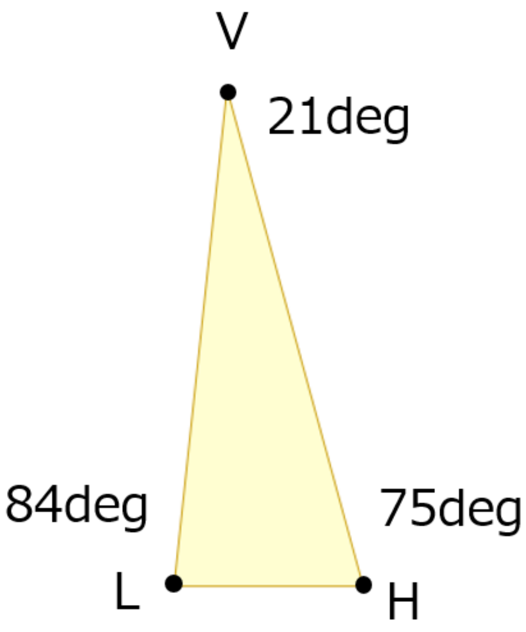


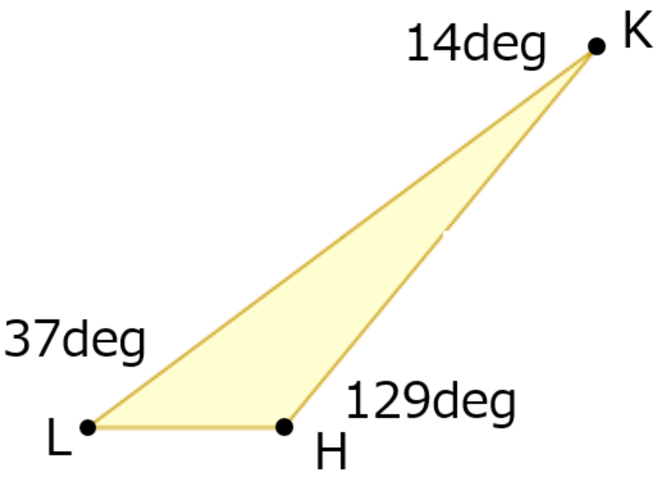
Comparison (HLV_sim) vs. (HLV_mbta)

Difference: from geometry

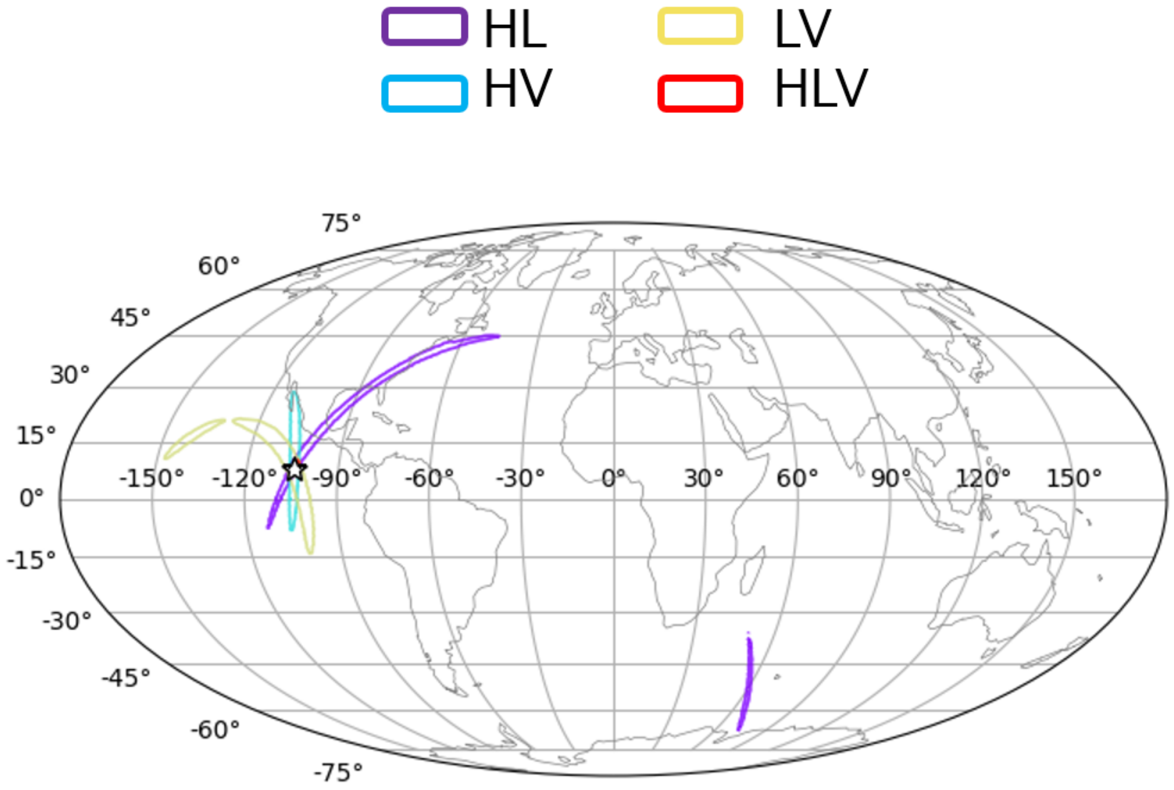


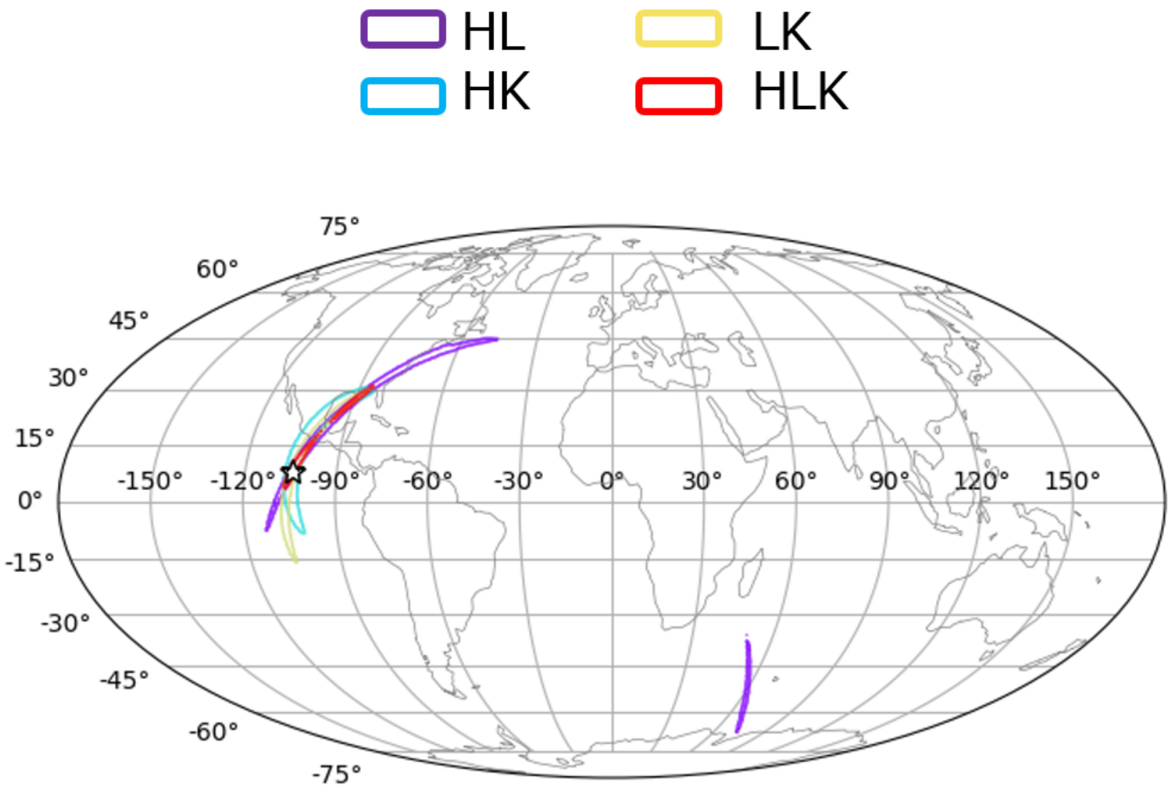
arXiv: 1304.0670





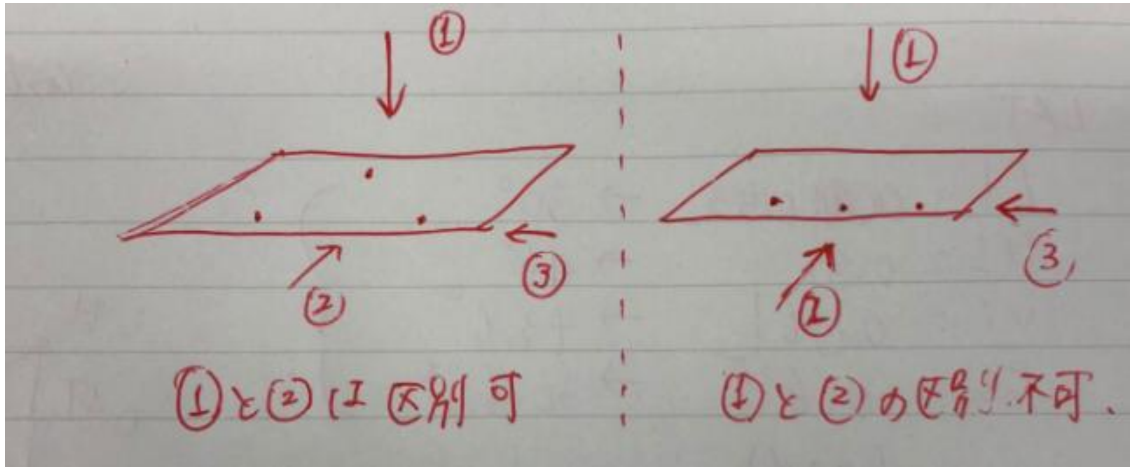
Difference: from geometry





Difference: from geometry

* Flatter triangle would make localization worse.



→ This effect could be could be evaluated by using:

https://arxiv.org/pdf/0908.2356.pdf
https://arxiv.org/pdf/1010.6192.pdf

$$p(\mathbf{r}|\mathbf{R}) \propto p(\mathbf{r}) \exp\left[-\frac{1}{2}(\mathbf{r}-\mathbf{R})^T \mathbf{M}(\mathbf{r}-\mathbf{R})\right]$$

$$\mathbf{M} = \frac{\mathbf{D}_{12}\mathbf{D}_{12}^T}{\sigma_{12}^2} + \frac{\mathbf{D}_{23}\mathbf{D}_{23}^T}{\sigma_{23}^2} + \frac{\mathbf{D}_{31}\mathbf{D}_{31}^T}{\sigma_{31}^2}. \qquad (30)$$

Thus $\mathbf{M}$ has a contribution from each pair of detectors which depends upon the detector separation $\mathbf{D}_{ij}$ and the pairwise timing uncertainty

$$\sigma_{ij}^2 = \sigma_i^2 + \sigma_j^2 + \frac{\sigma_i^2\sigma_j^2}{\sigma_k^2} \qquad (31)$$

where $k \neq i, j$. The timing uncertainty from a given pair of detectors is dependent upon the timing accuracy σ_k in the third detector. Initially, this may seem surprising,

M: for the localization accuracy based on the detector geometry & timing accuracy.

→ det(M_HLV) / det(M_HLK) ~ 2

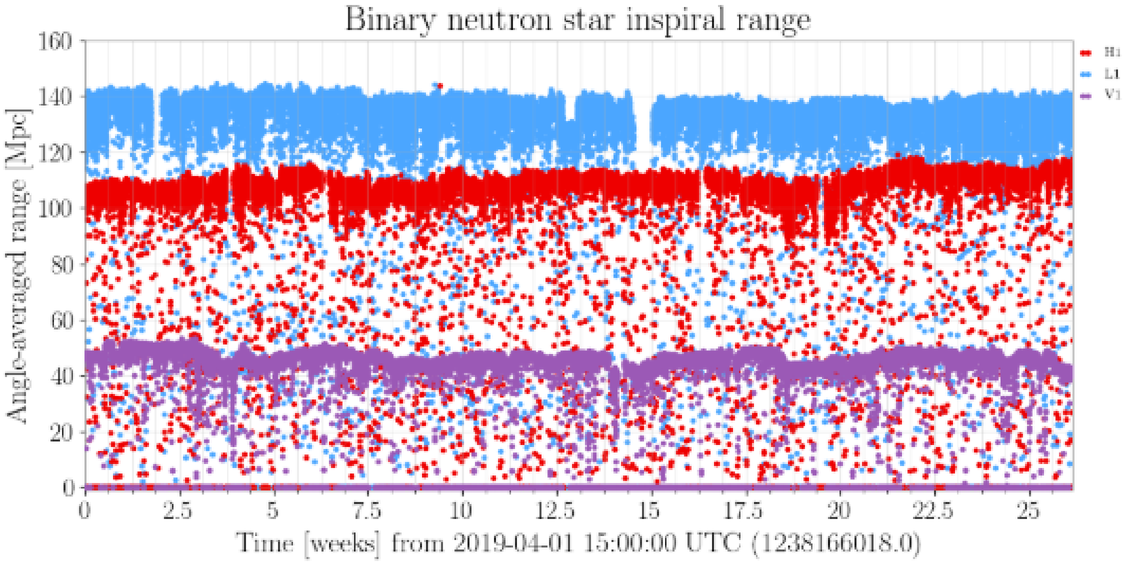
Actual duty cycle:

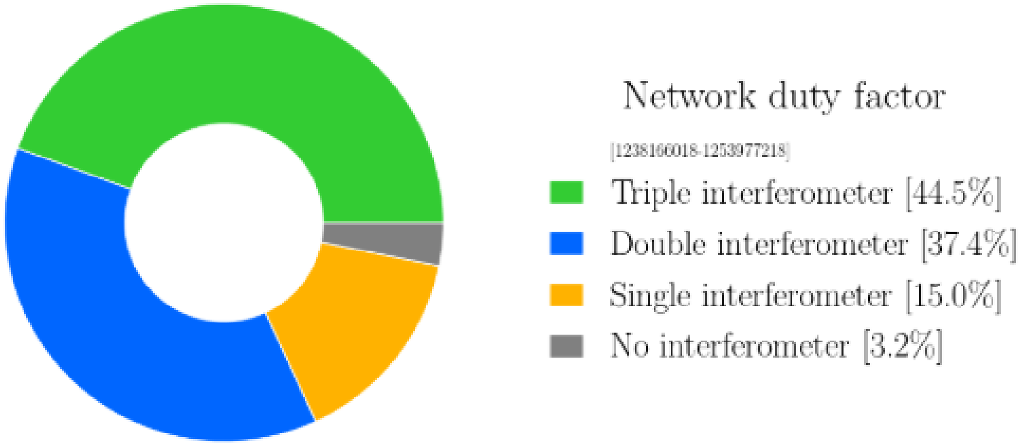
Table 1 Percentage of time during the first and second observing runs that the aLIGO and AdV detectors spent in different operating modes as recorded by the on-duty operator. Since several factors may influence detector operation at any given time, there is a certain subjectivity to the assignments. Maintenance includes a planned 4-h weekly period (~ 2.4% of the total), and unplanned corrective maintenance to deal with equipment or hardware failures. Coincident operation of the aLIGO detectors occurred ~ 43% of the time in O1 and ~ 46% in O2. After joining O2 on August 1 2017 AdV operated with a duty factor of approximately 85% until the end of the run on August 25 2017.

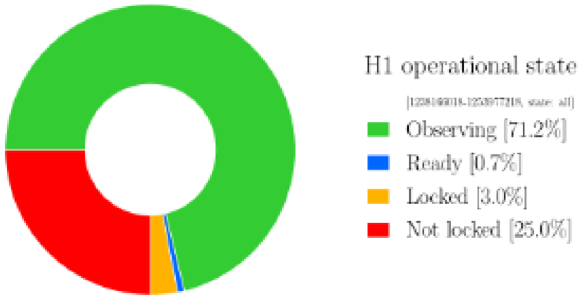
		O1		O2		
		Hanford	Livingston	Hanford	Livingston	Virgo
Operating mode %	Observing	64.6	57.4	65.3	61.8	85.1
	Locking	17.9	16.1	8.0	11.7	3.1
	Environmental	9.7	19.8	5.8	10.1	5.6
	Maintenance	4.4	4.9	5.4	6.0	3.1
	Commissioning	2.9	1.6	3.4	4.7	1.1
	Planned engineering	0.1	0.0	11.9	5.5	–
	Other	0.4	0.2	0.2	0.2	2.0

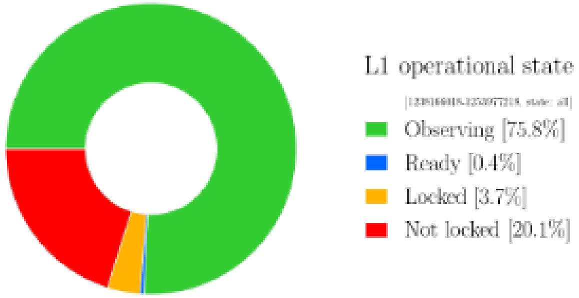
Actual performance of online detectors:

https://summary.ligo.org/~detchar/summary/O3a/

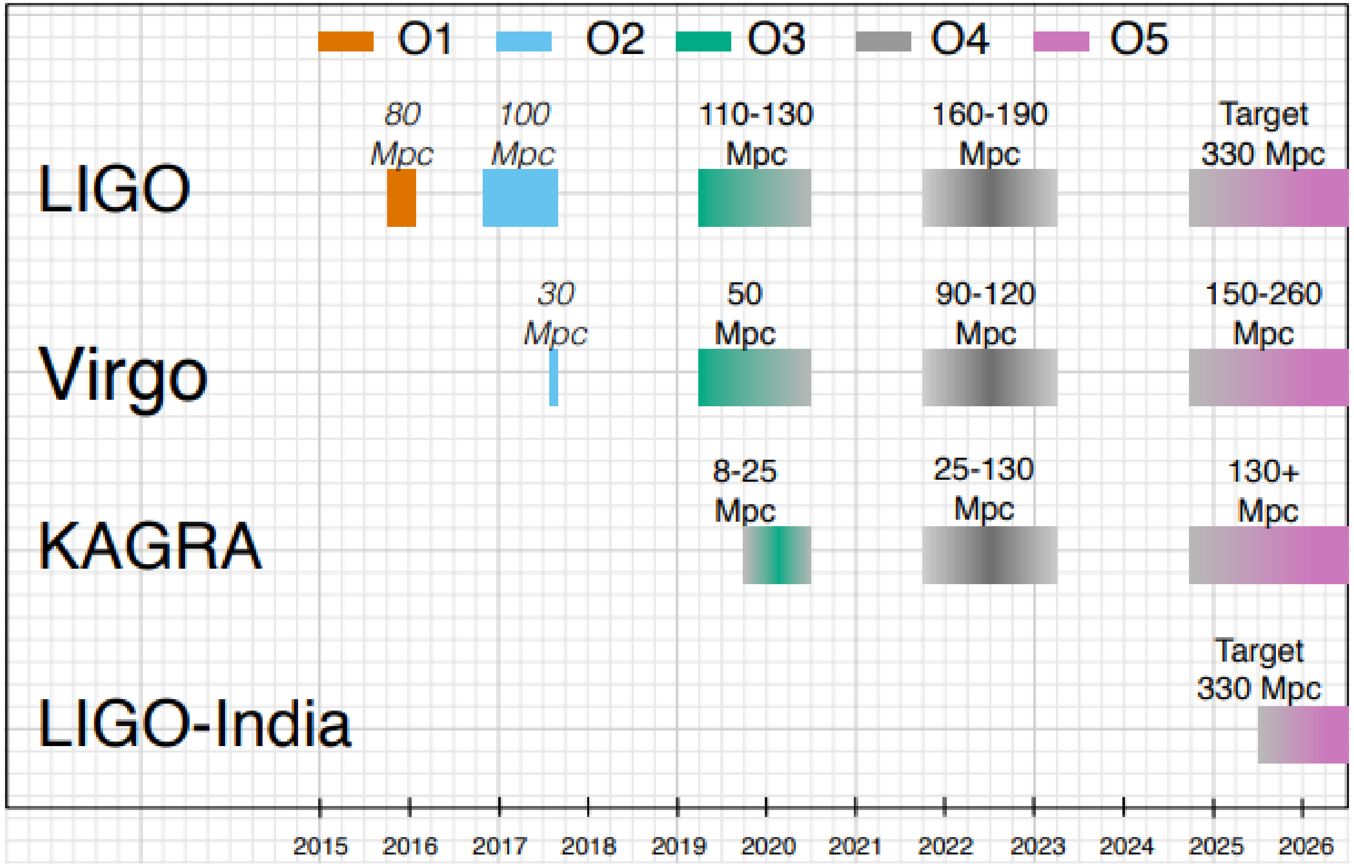




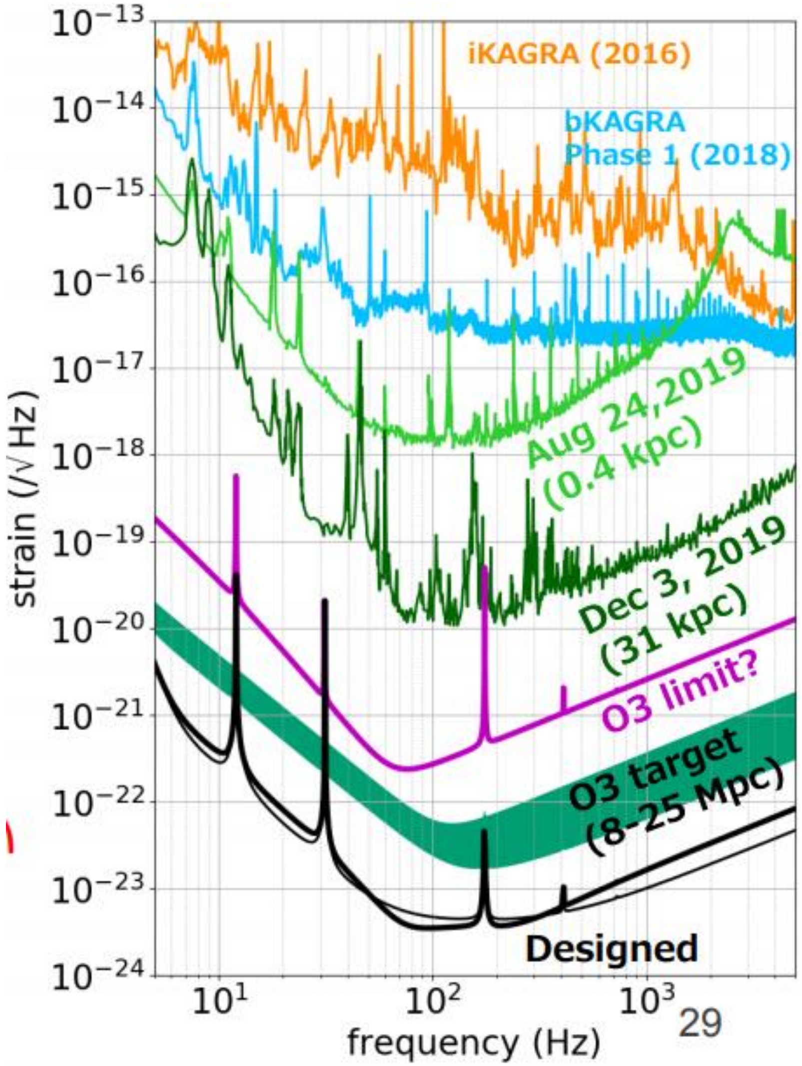




Prospects for observation & current KAGRA



arXiv: 1304.0670



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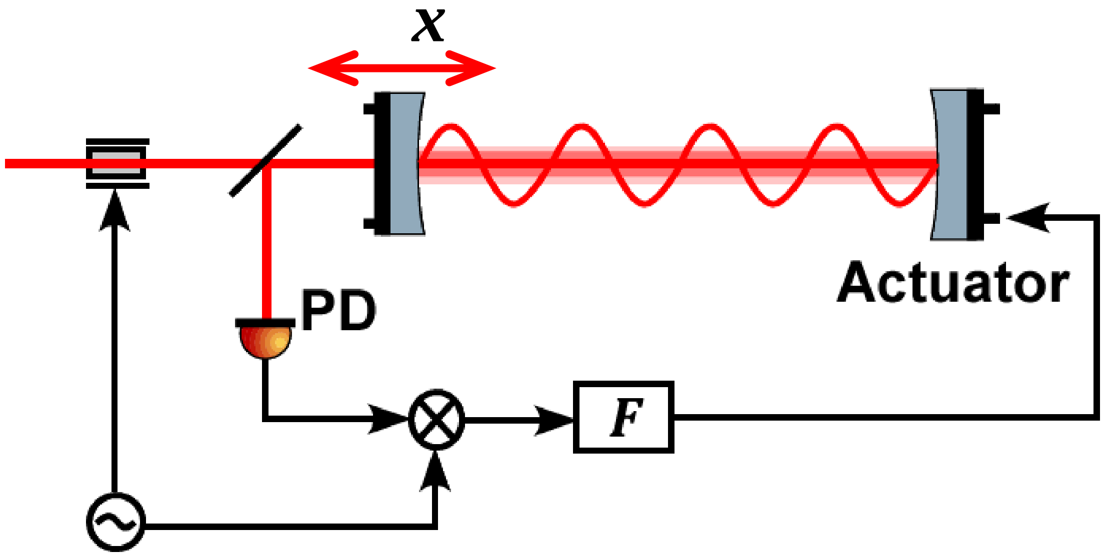
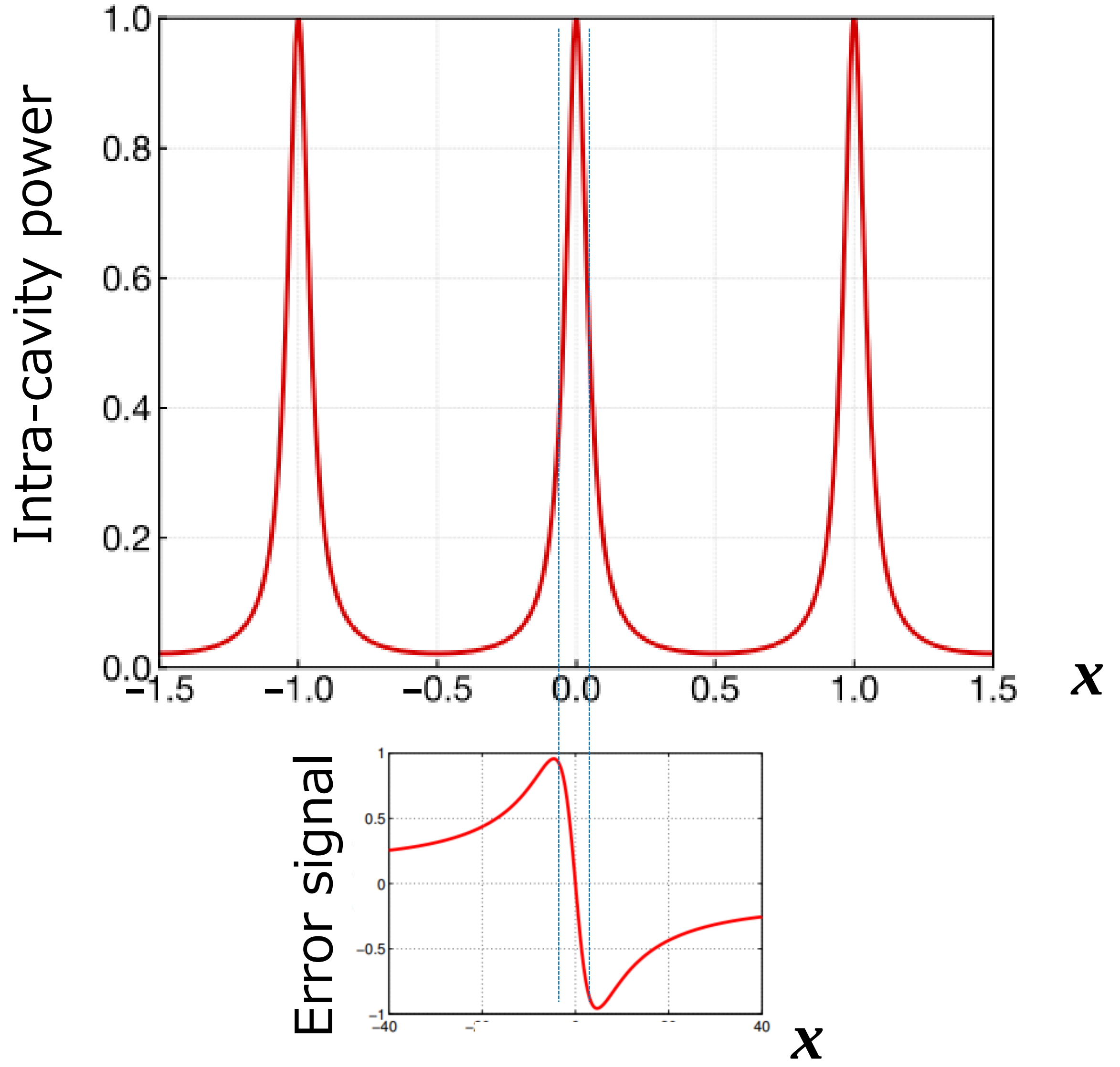
JGW-G1911123

Interferometer locking:

Pound-Drever-hall (PDH) technique:

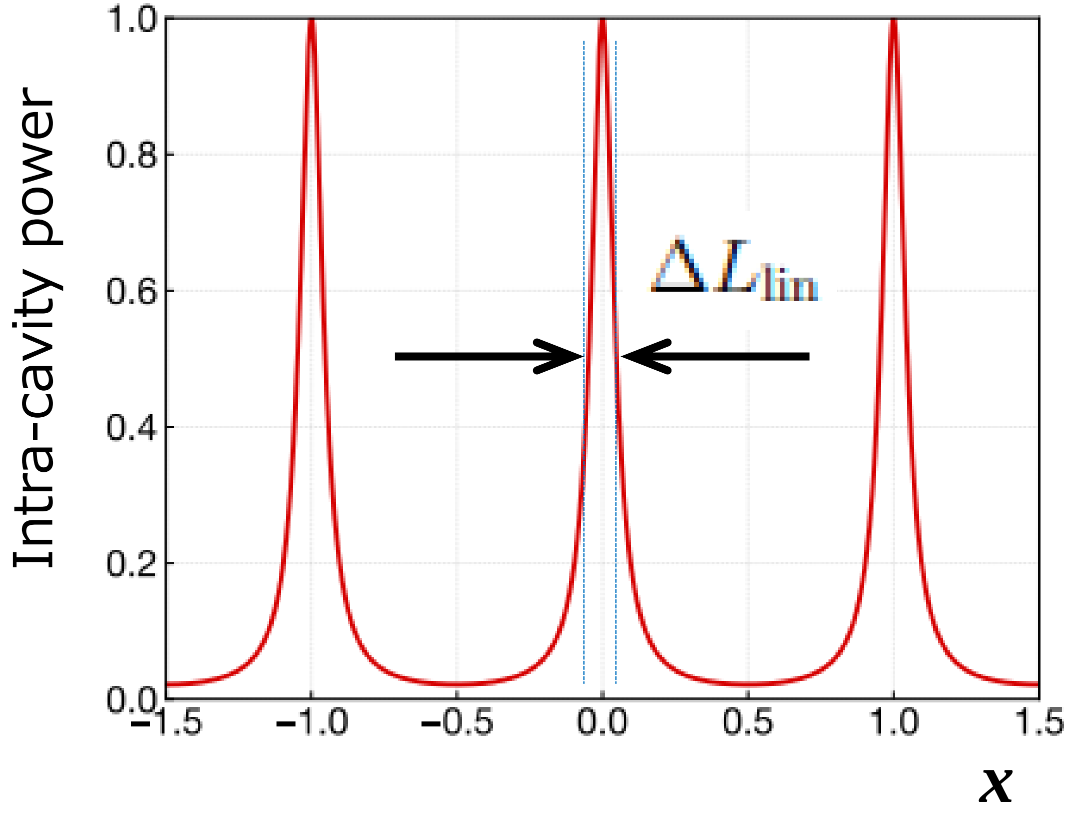


[ref] https://gwdoc.icrr.u-tokyo.ac.jp/cgi-bin/private/DocDB/ShowDocument?docid=4739

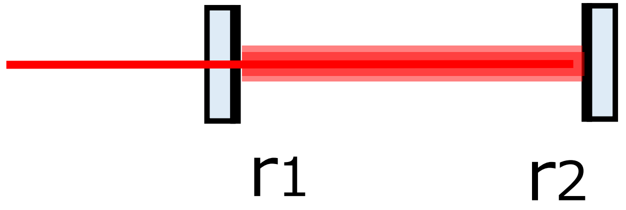


Feedback control only works within linewidth (FWHM).

Cavity linewidth:



$$\Delta L_{\rm lin} = \frac{\lambda}{2\mathcal{F}}. \qquad \left(\mathcal{F} = \frac{\pi\sqrt{r_1 r_2}}{1 - r_1 r_2}.\right)$$



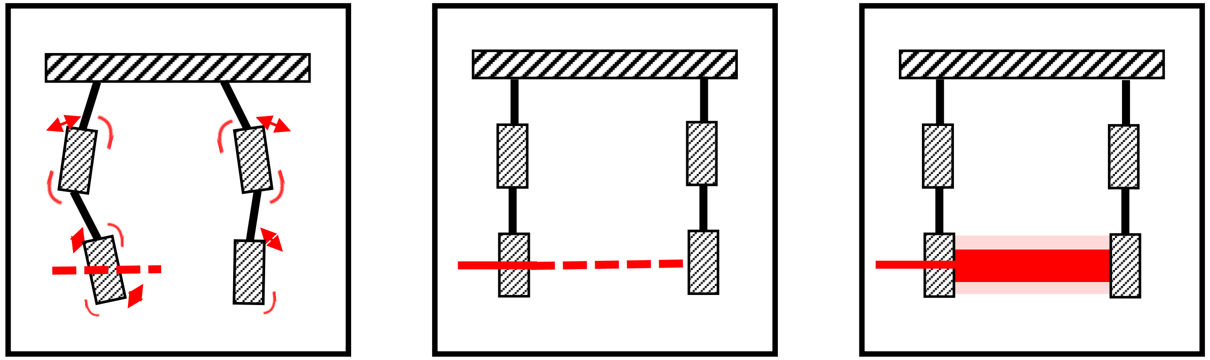
wb*del_L_lin = (2*pi*UGF)*lumbda/2/F

DoFs	UGF [Hz]	Finessse	lambda [nm]	wb*del_L_lin [um/s]	del_L_lin [nm]
ARM_IR		1550	1064		0.34
ARM_GR	10e3	50	532	334	53.24
MICH	50 for BS	1	1064	167	226
PRCL	50 for PRM	57	1064	2.93	9.33
SRCL	50 for SRM	38	1064	4.398	14

My work for Type-A:

Local control system

Implementation & Performance test



Res. damping Lock-acq. Observation

With full Type-A: **My work**

Goal:

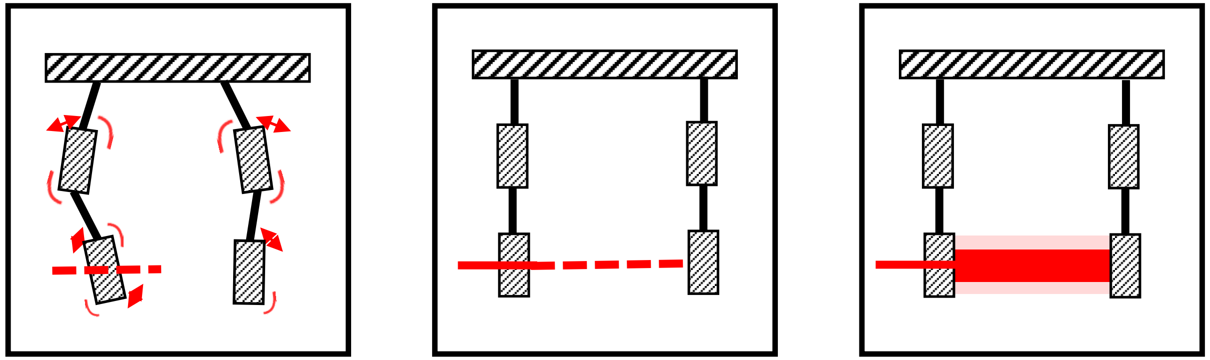
To construct local control system of full Type-A to allow interferometer locking.

* Control system in observation:
→ much depends on interferometer control (*global control*) in addition.
→ set as future work.

My work for Type-A:

Local control system

Implementation & Performance test



Res. damping　Lock-acq.　Observation

With full Type-A: **My work**

Data acq. system & digital system

Mechanical system

Already done

Goal:

To construct local control system of full Type-A to allow interferometer locking.

* Control system in observation:
→ much depends on interferometer control (*global control*) in addition.
→ set as future work.

What has been already done & not done for Type-A:

Mechanical system

Basic designing

<u>Suspension system:</u>
[T. Sekiguchi internal doc.(2014)]+

<u>Cryogenic system:</u>
[D. Chen PhD thesis(2015)+

Installation (& characterization)

<u>Room-temp. part:</u>
[K. Okutomi PhD (2019)]

<u>Cryogenic temp. part:</u>
[T. Yamada master's(2018)]+
[CQG **36** (2019) 165008]+

Data acq. system & digital system

[PTEP (2018) 013F01]+

Room-temp. part

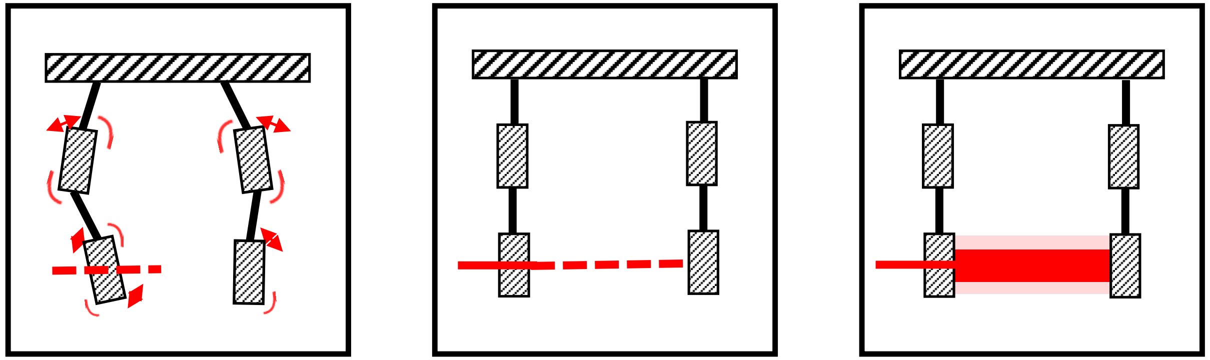
Cryogenic-temp. part

Basic mechanical-system development
→ Already finished.

What has been already done & not done for Type-A:

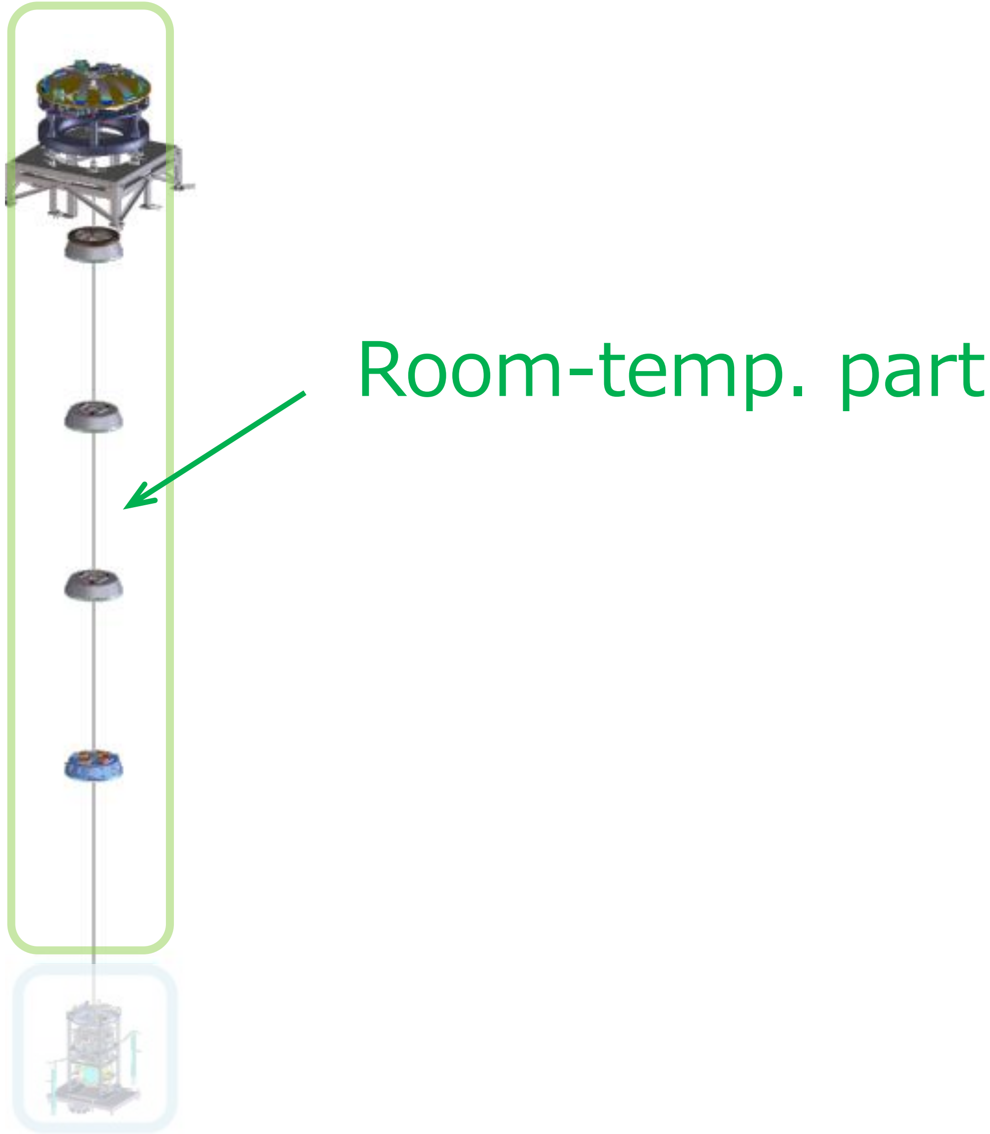
Local control system

Implementation & Performance test



Res. damping Lock-acq. Observation

With room-temp. part:
[K. Okutomi PhD (2019)](*1)

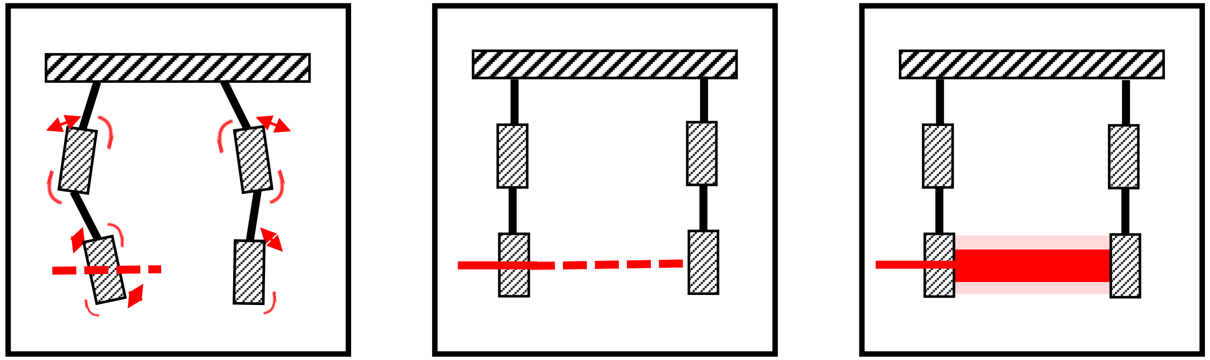


(*1) for arm-cavity lock.

What has been already done & not done for Type-A:

Local control system

Implementation & Performance test



Res. damping   Lock-acq.   Observation

With room-temp. part:
[K. Okutomi PhD (2019)](*1)

With full Type-A: **My work**

(*1) for arm-cavity lock.

Goal:

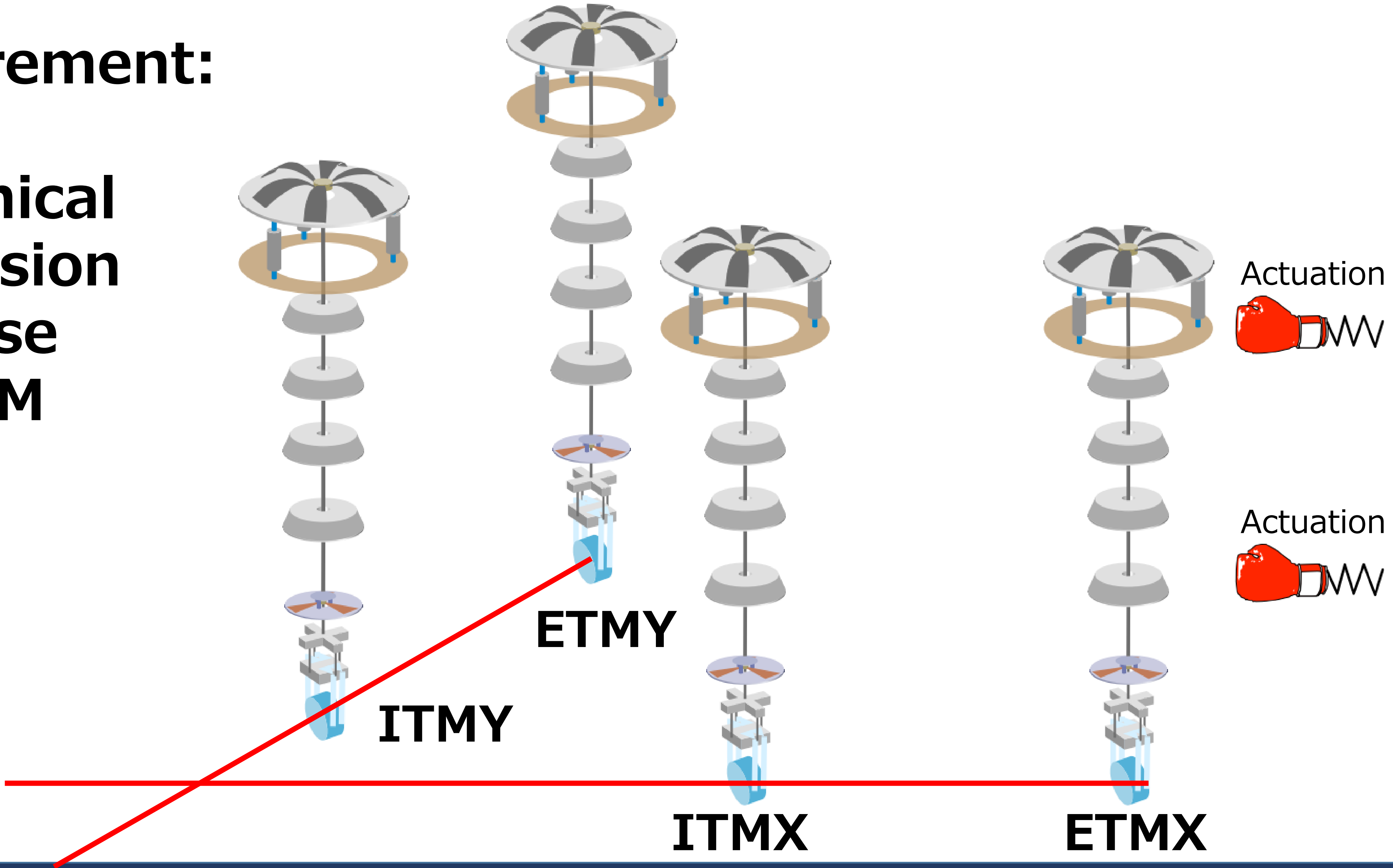
To construct local control system of full Type-A for acquiring interferometer lock.

* Control system in observation:
→ much depends on interferometer control (*global control*) in addition.
→ set as future work.

Note: verification of suspension performance

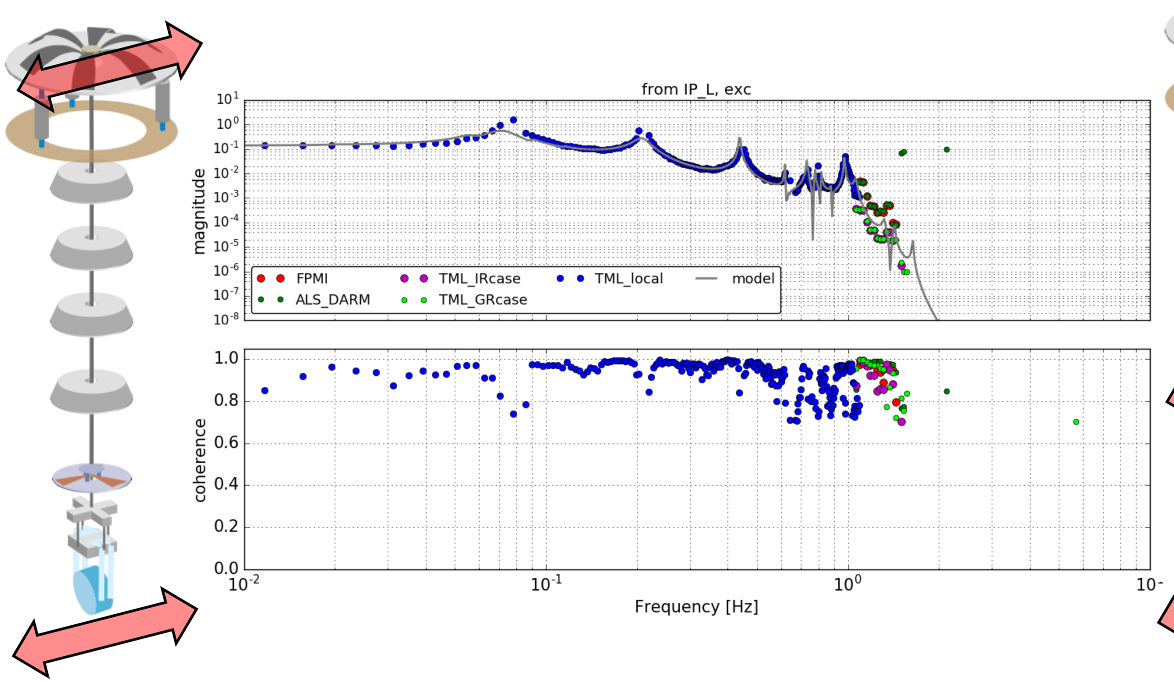
Measurement:

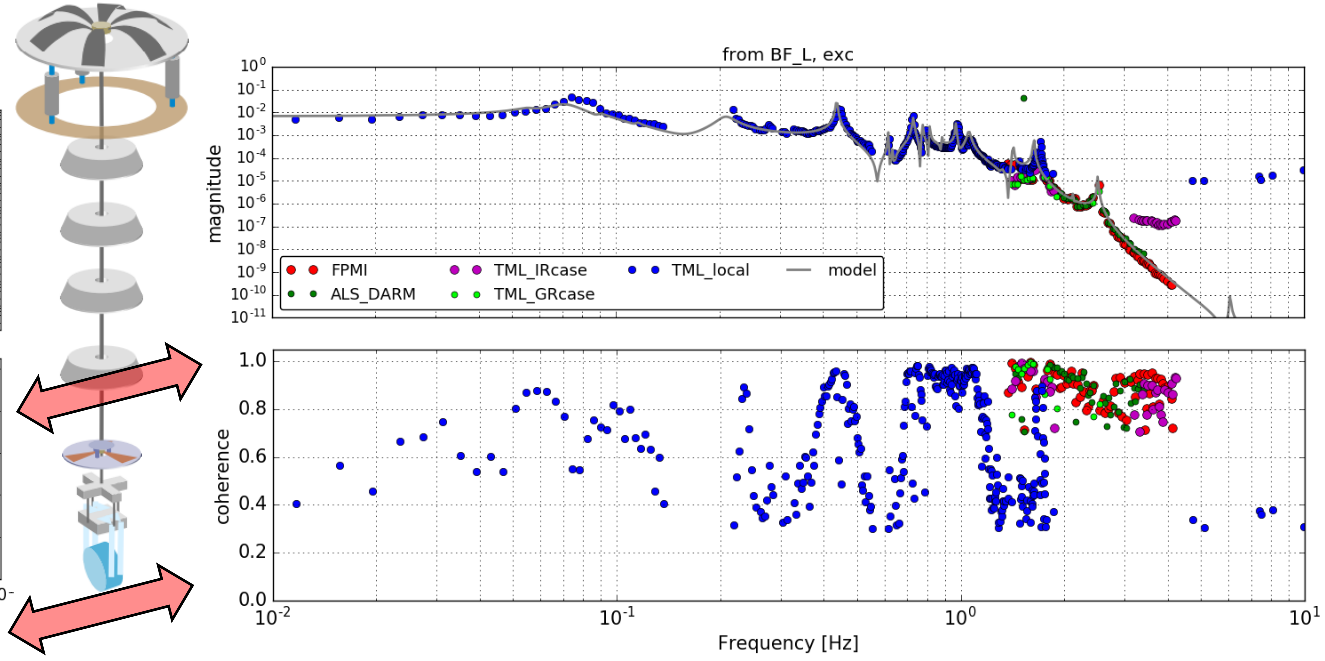
Mechanical suspension response to DARM



1. Mechanical system characterization:

* By checking vibration isolation

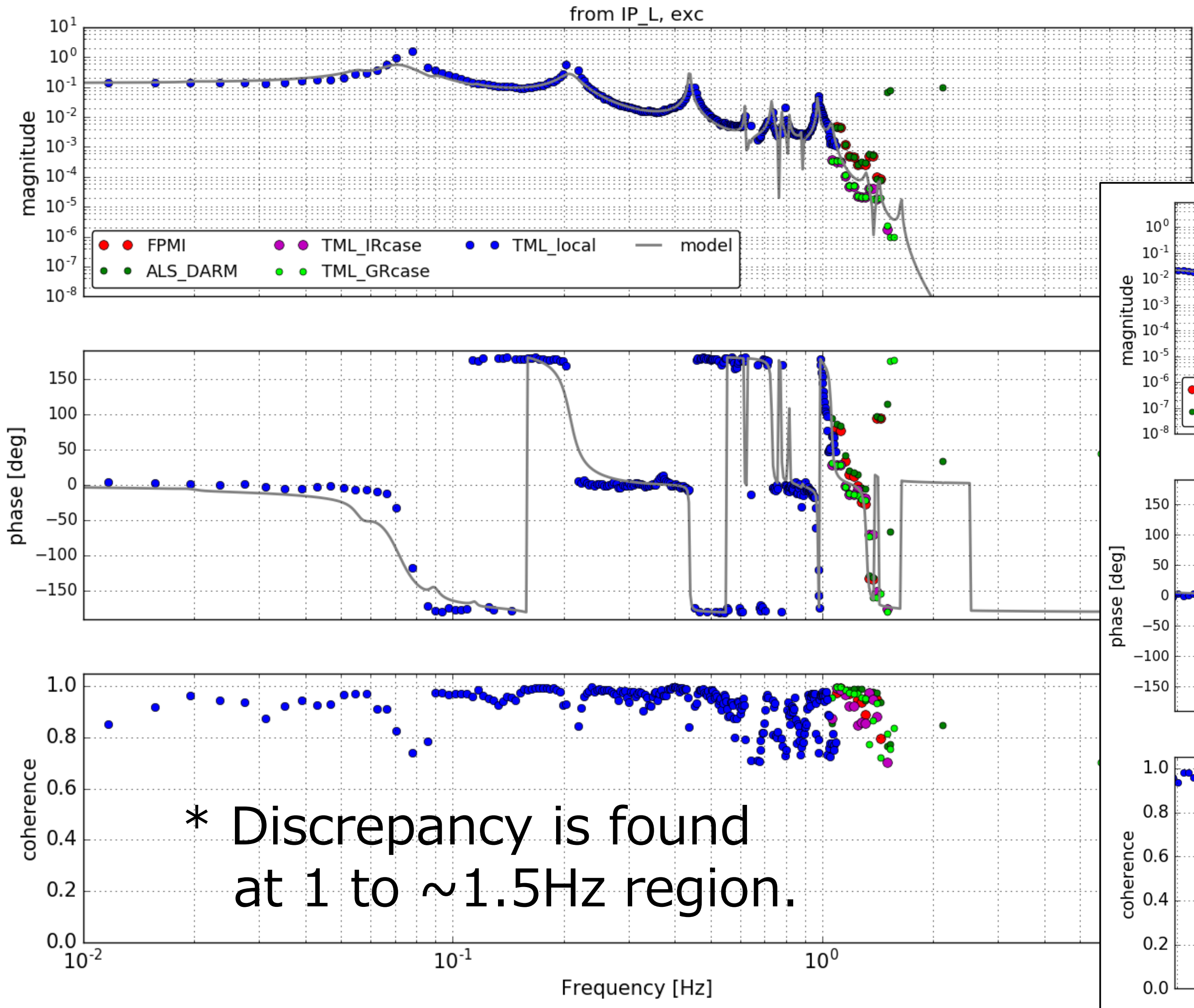




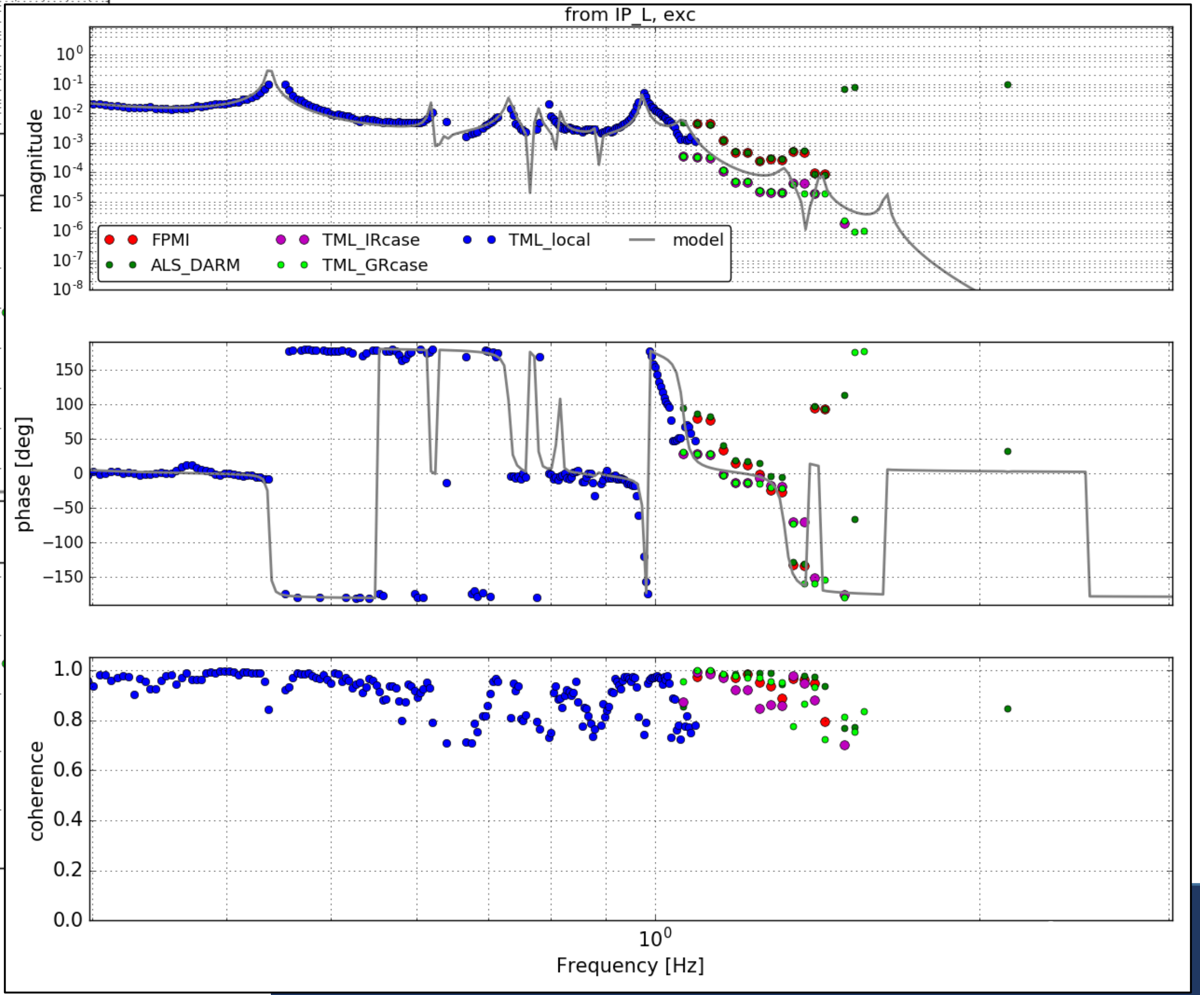
→ **Type-A suspension has characteristics of pendulum up to 4 Hz.**

→ discrepancy at 1 Hz to 1.4 Hz is worth to investigate for further improvement.

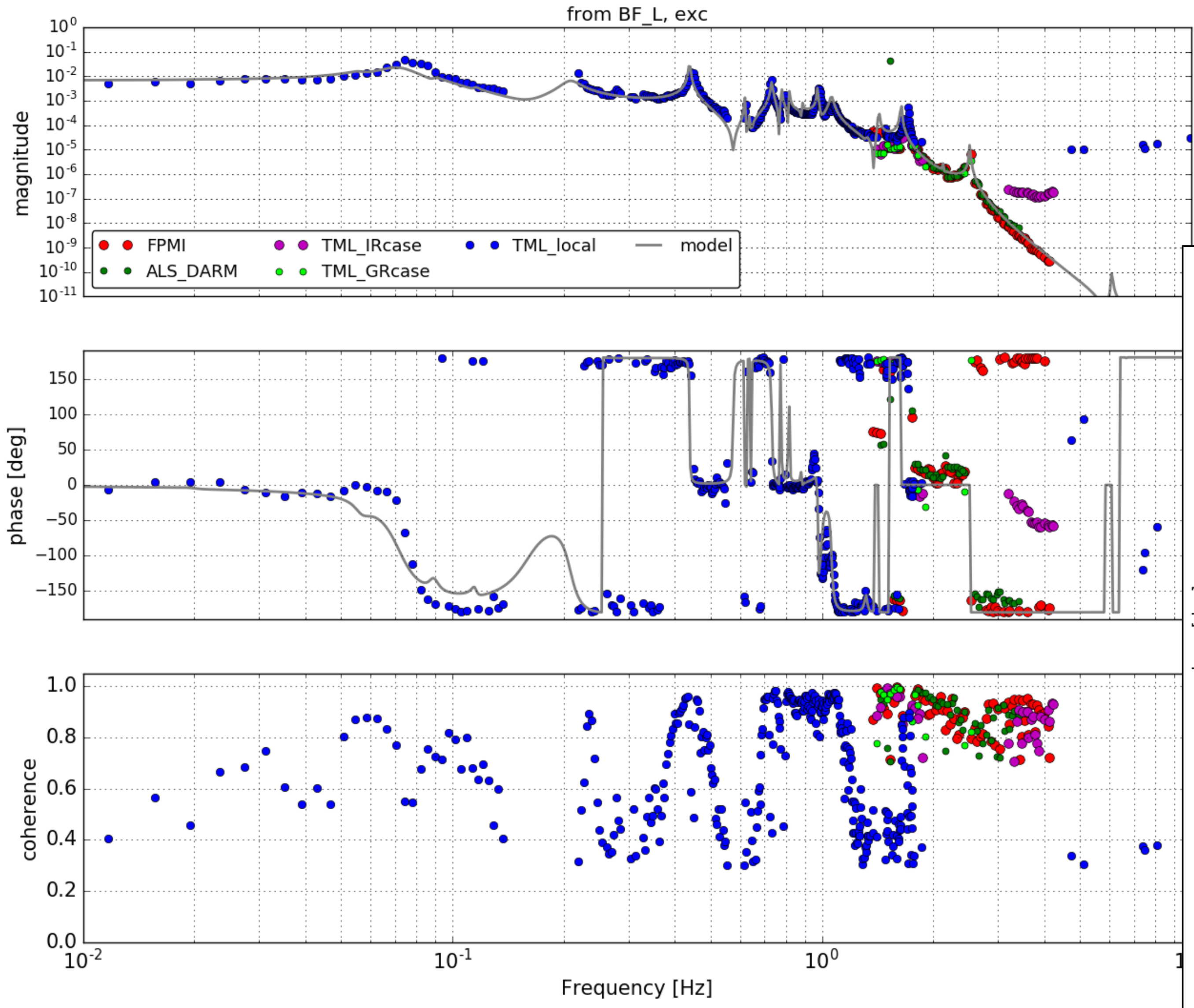
Results: force transfer functions, from IPL



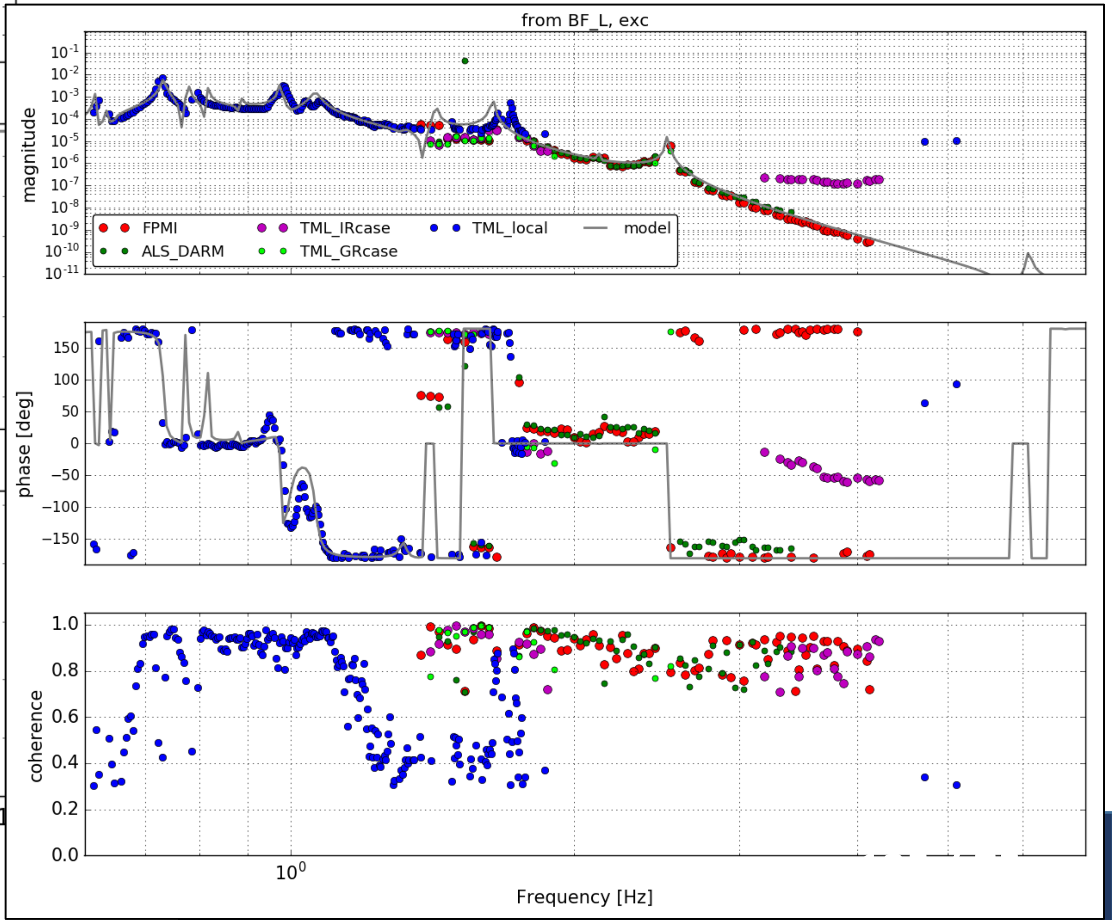
* Discrepancy is found at 1 to ~1.5Hz region.



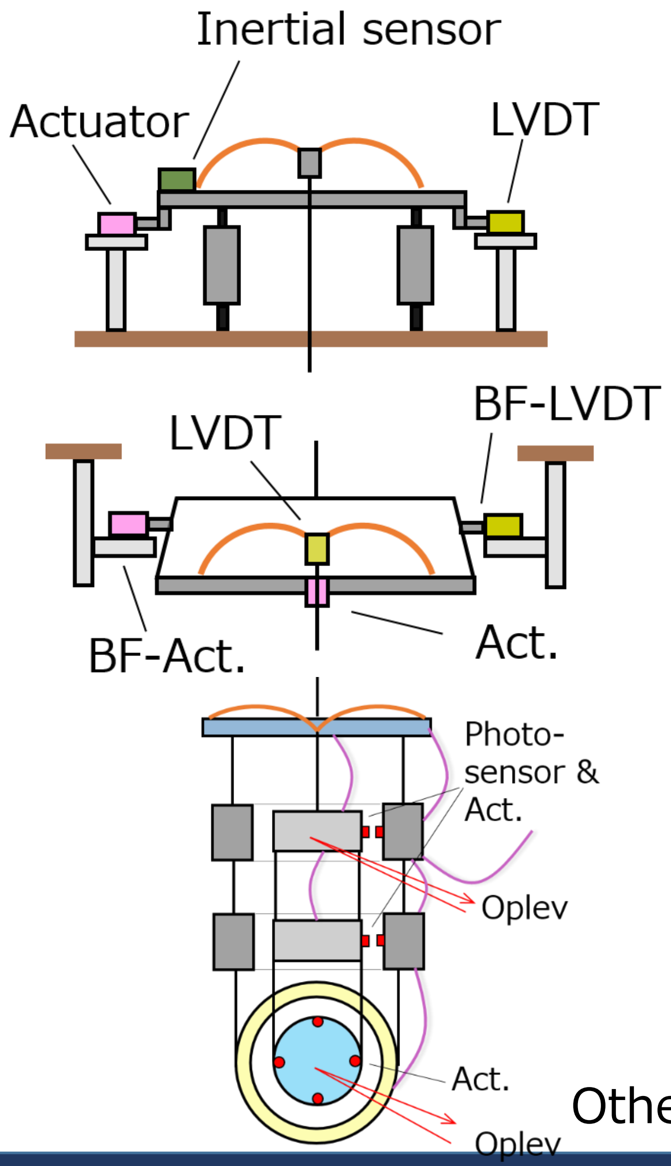
Results: force transfer functions, from BFL



The transfer function up to 4.2 Hz agree with the model.

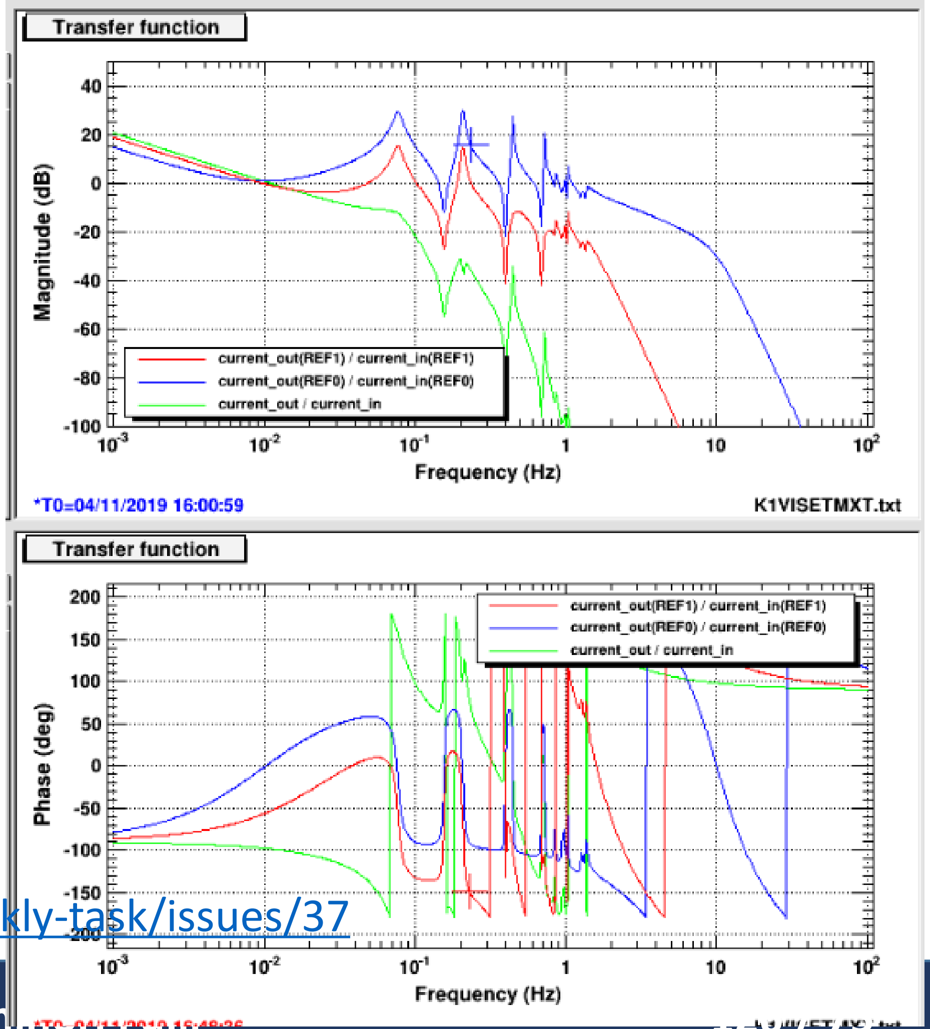


Settings for the measurement w/o controls:



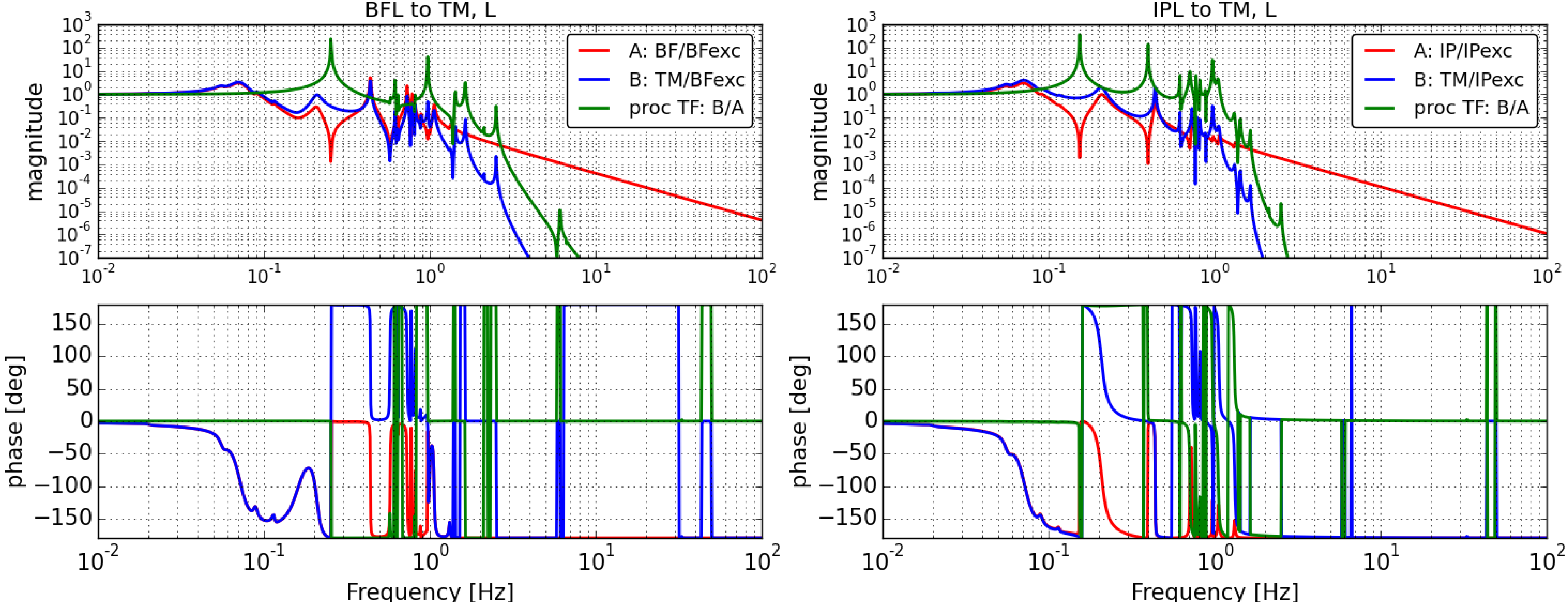
With Tower-damped state,

- ordinal L-loop (blue) was opened at IP satge.
- instead,
  - green curve loop was used for the ALS_DARM measurement,
  - red curve loop was used for the FPMI_DARM measurement.



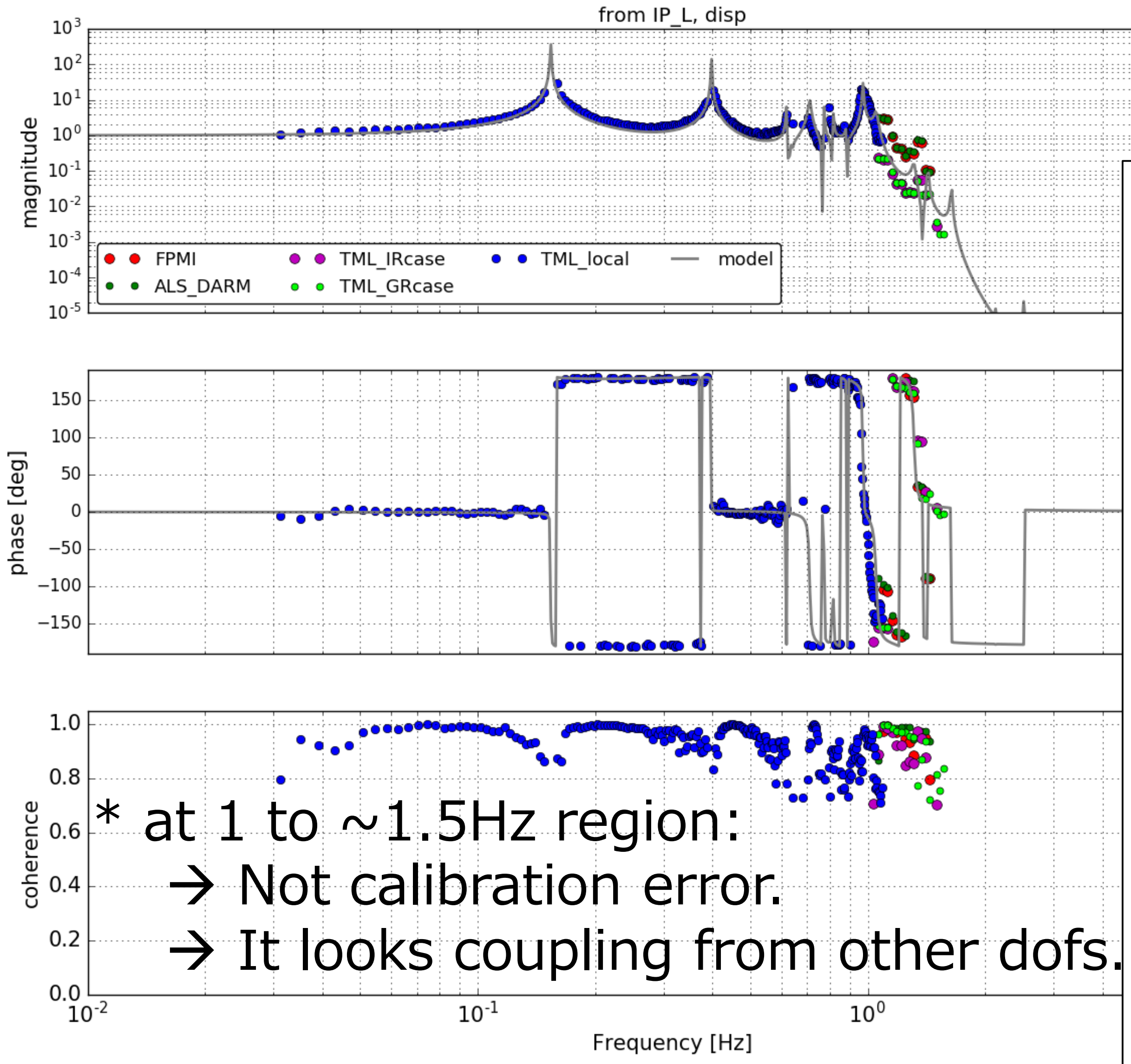
Other ref: https://github.com/YoshinoriFujii/Weekly-task/issues/37

Simulation models:

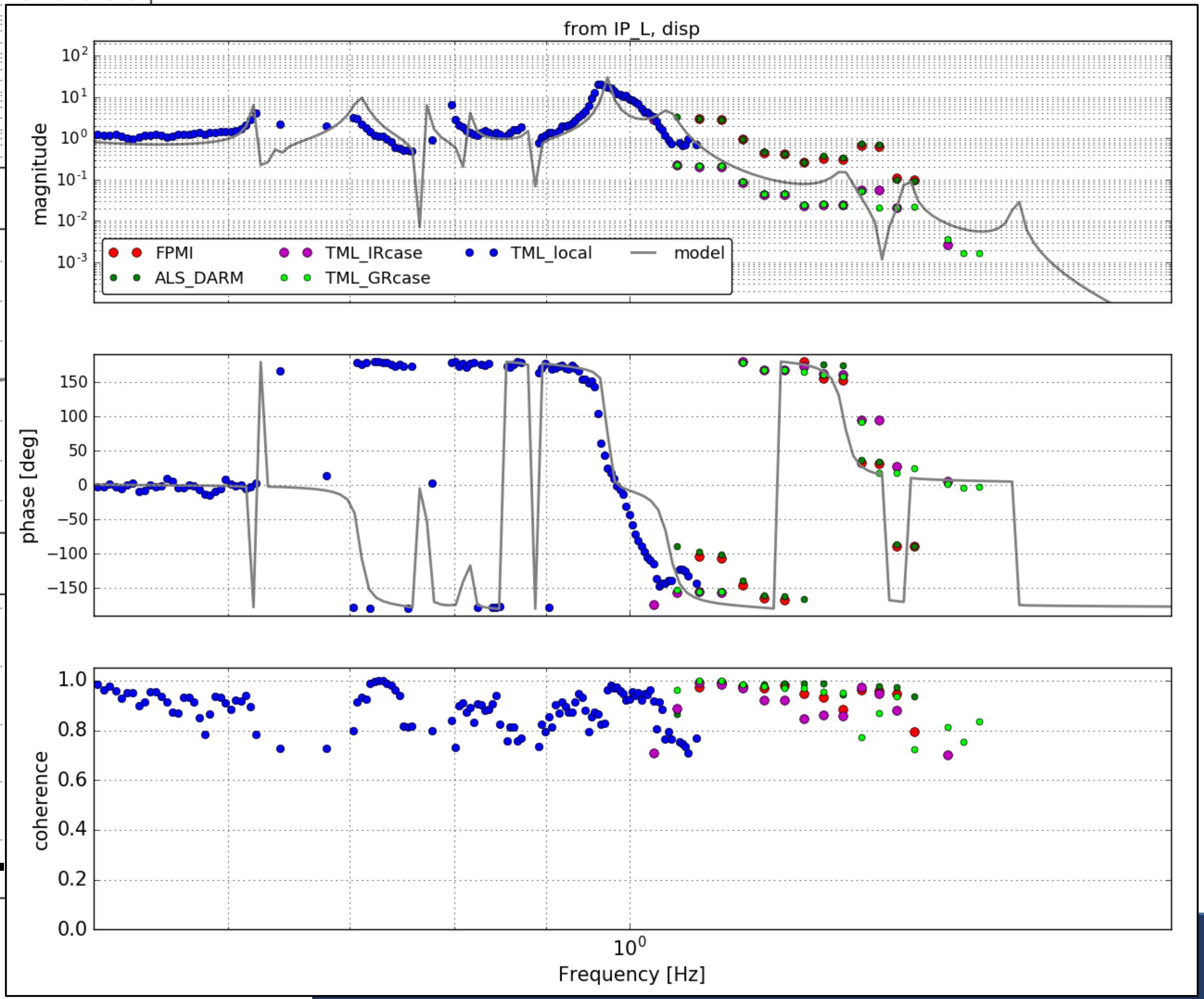


Results: displacement transfer functions, from IPL

It seems that model have to be tuned at 1 to ~1.5Hz region.

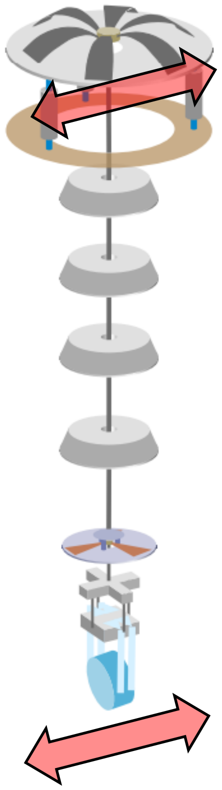


* at 1 to ~1.5Hz region:
→ Not calibration error.
→ It looks coupling from other dofs.

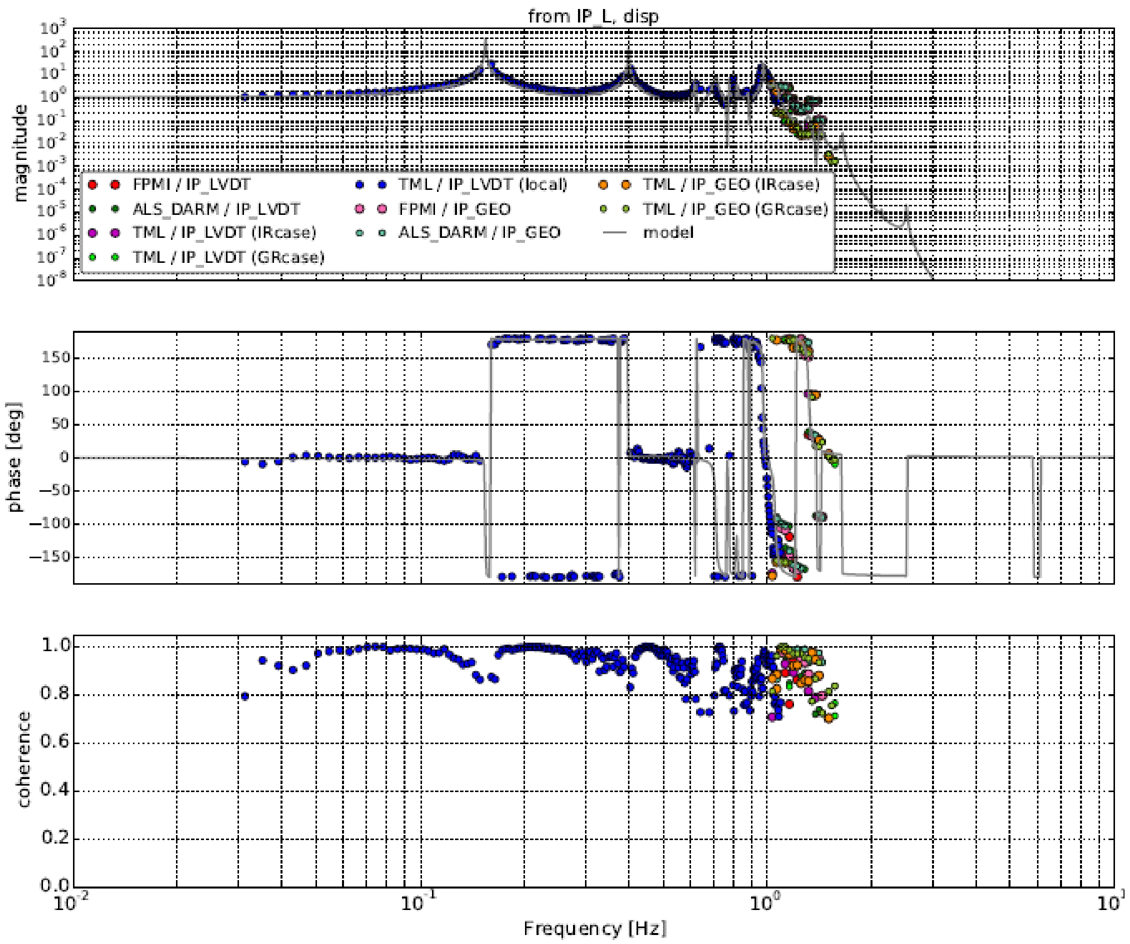


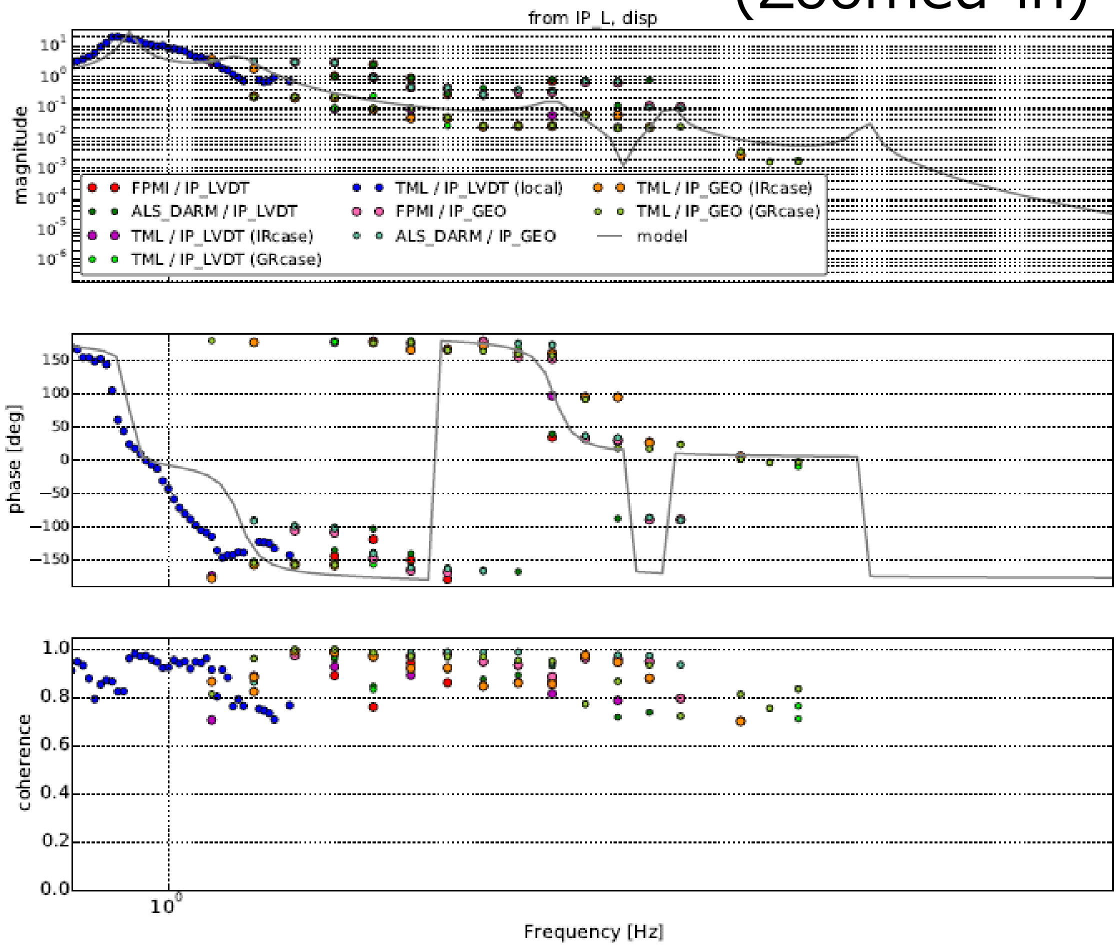
Results: displacement transfer functions, from IPL

* Including IP(geo) signal.

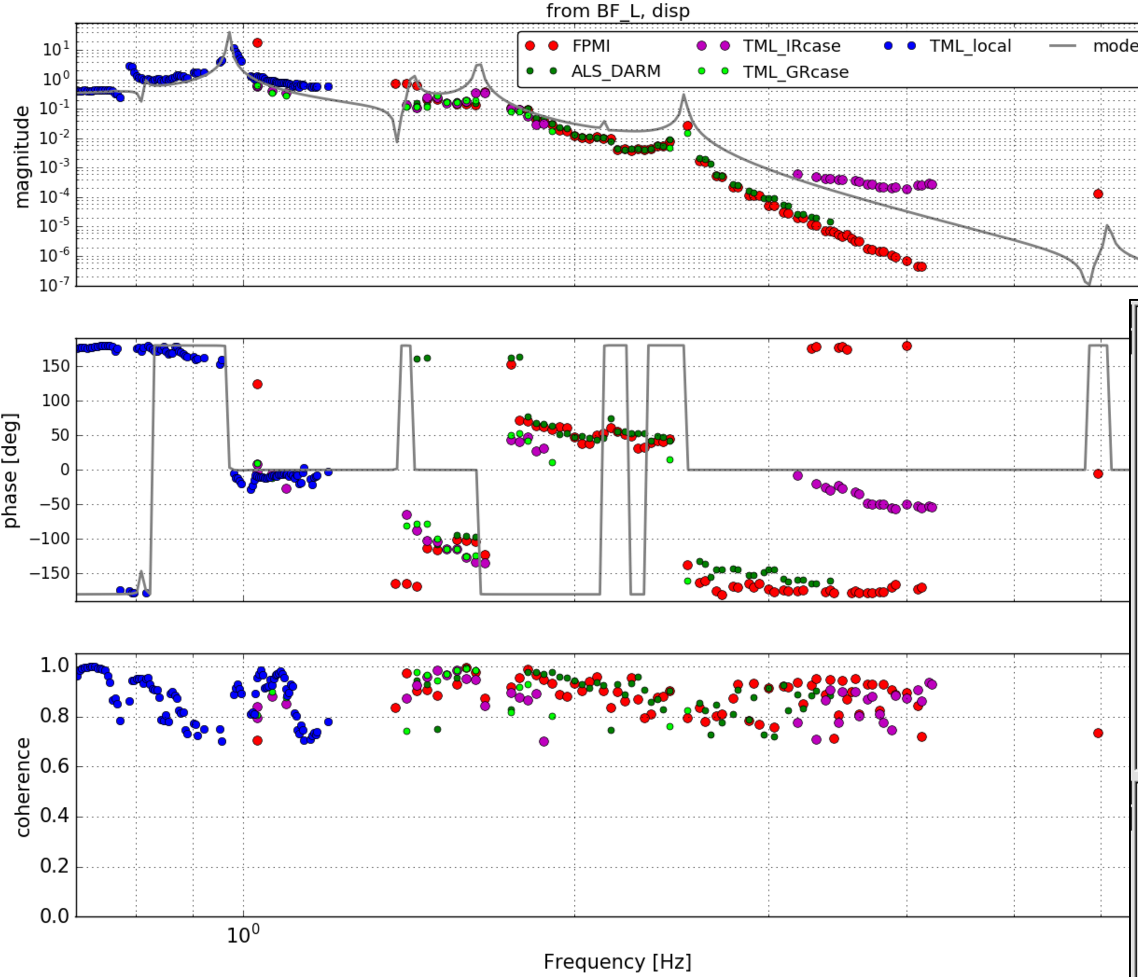


(Zoomed-in)

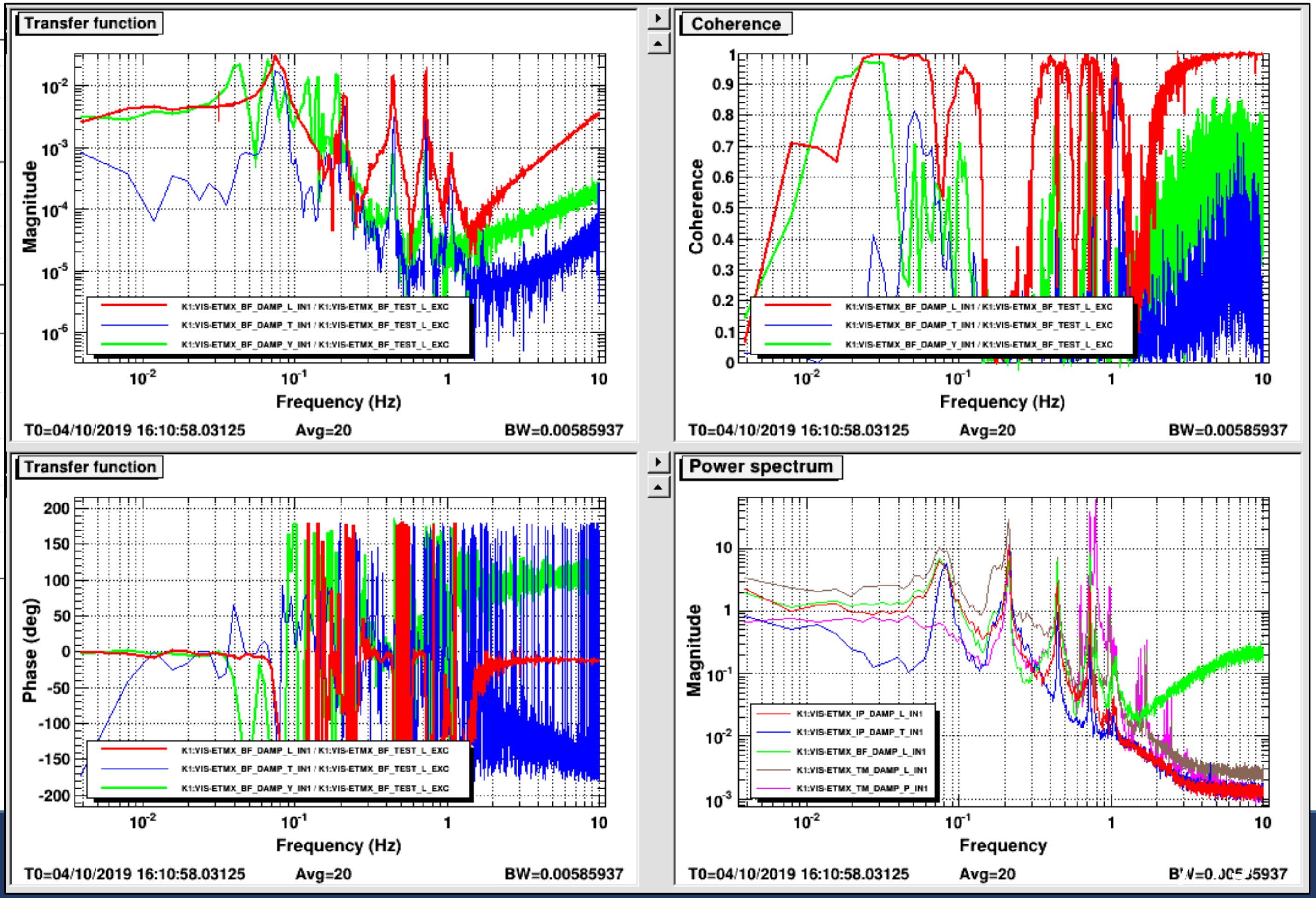




Results: displacement transfer functions, from BFL

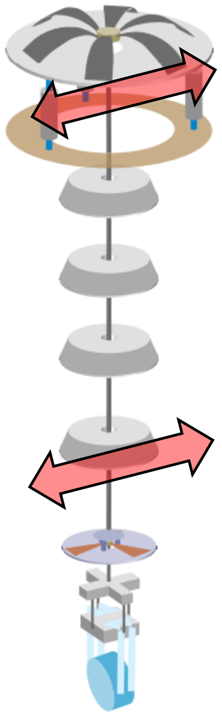


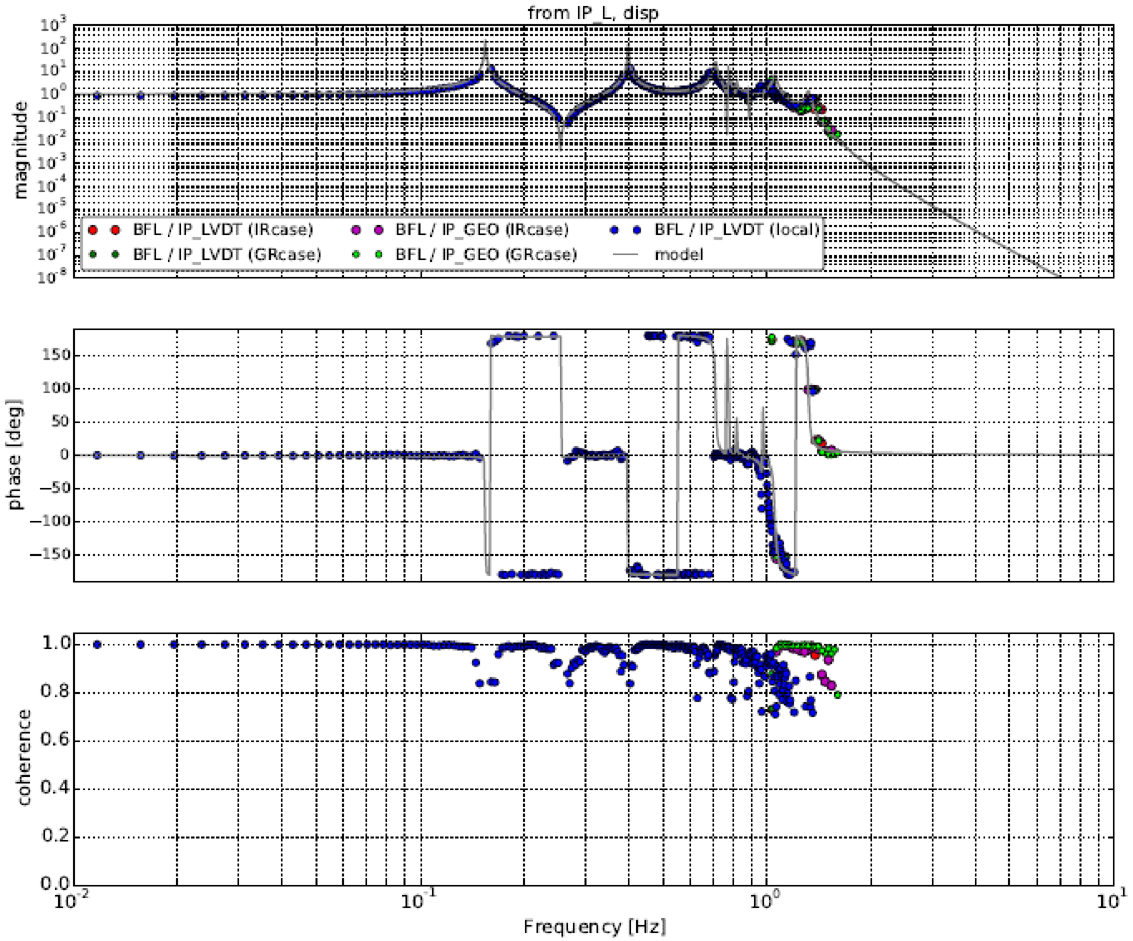
It seems that the discrepancy comes from the issue of LVDT, the direct sensor-actuator coupling.



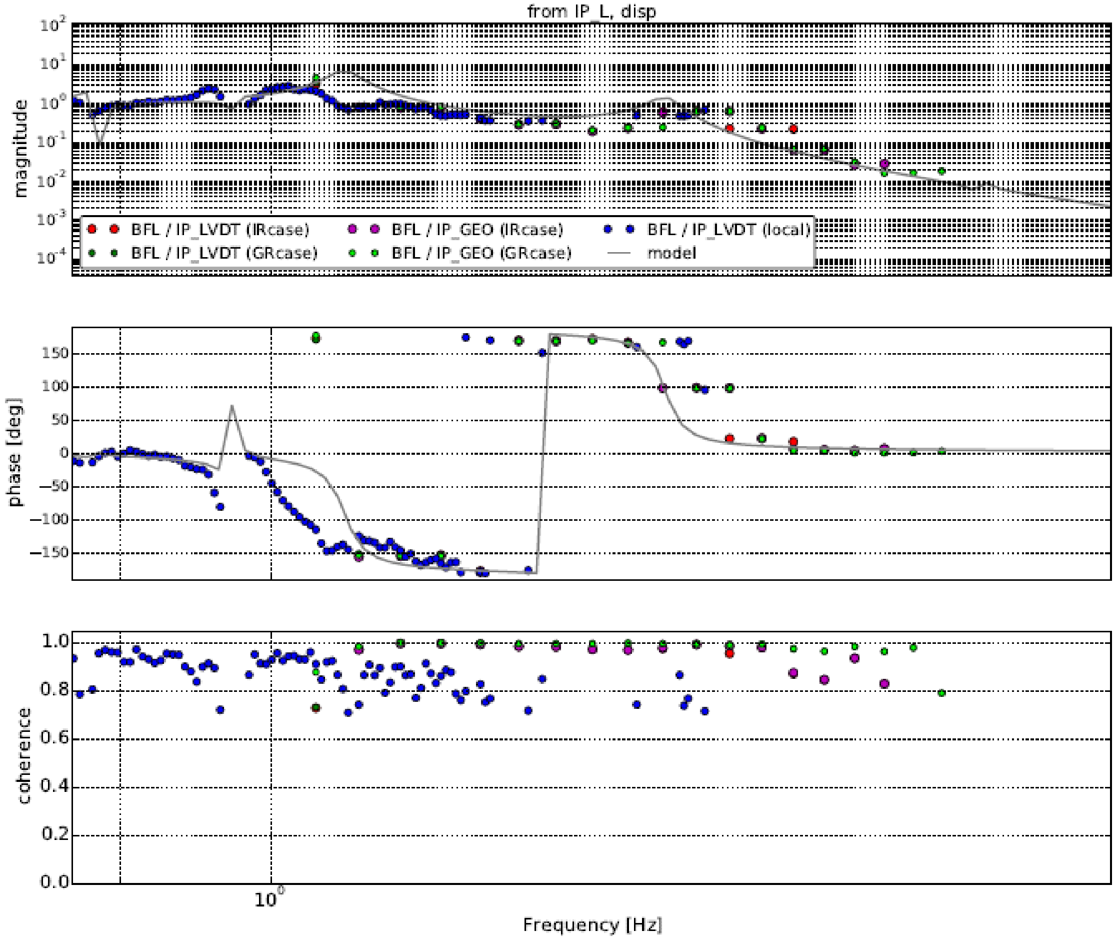
→ Not reliable.

Results: displacement transfer functions, from IPL to BFL





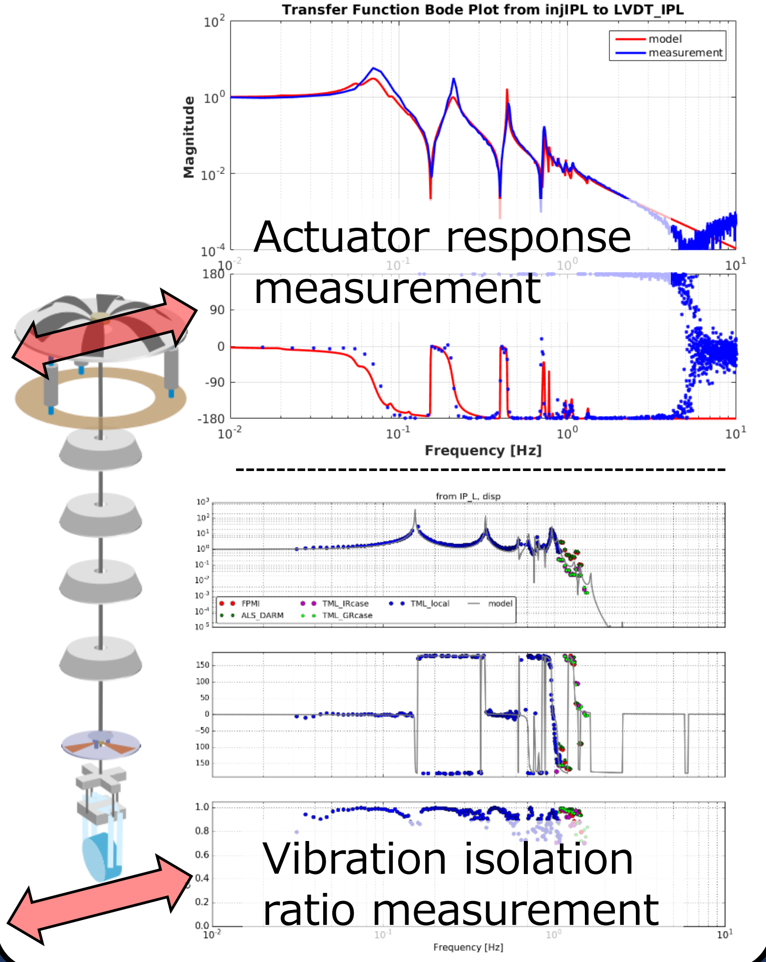
Including IP(geo) signal.



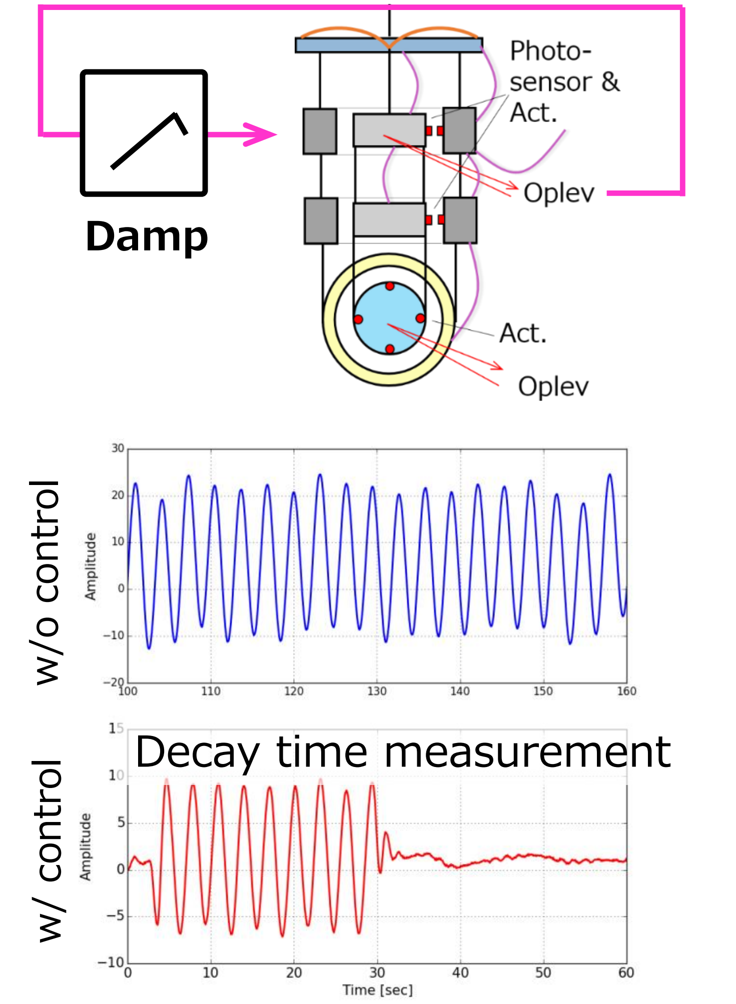
Notes: Resonance damping

My work: Constructing controls toward interferometer lock

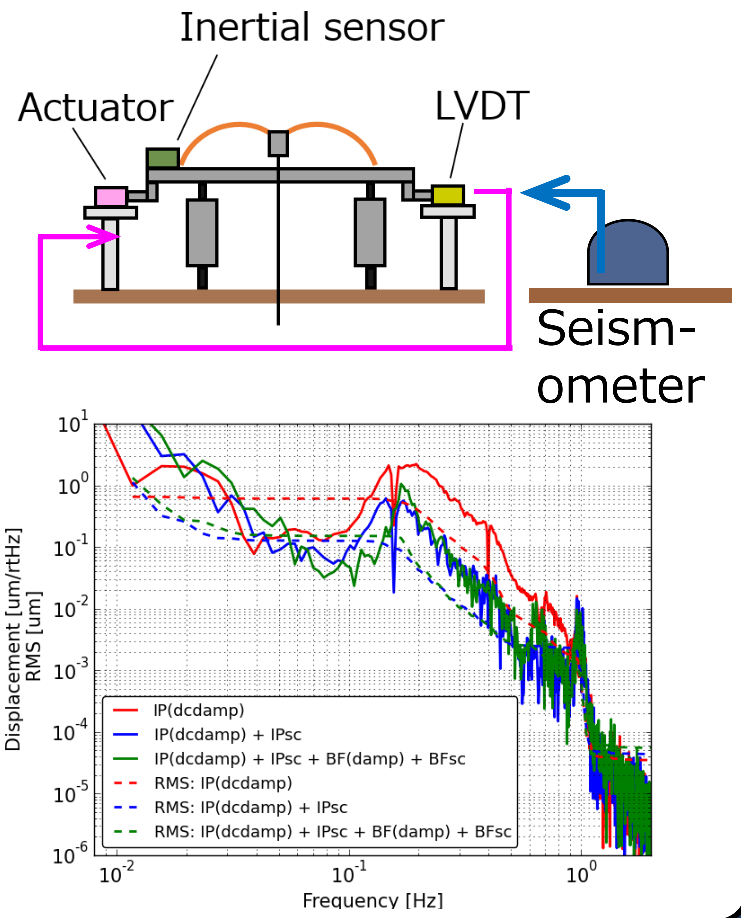
1. Mechanical system characterization



2. Resonance damping

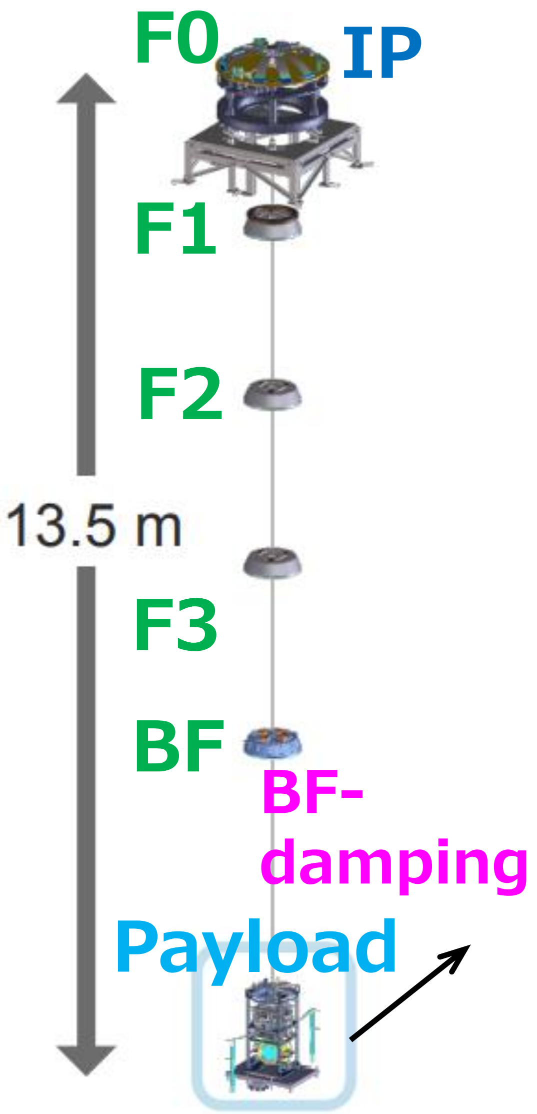


3. Mirror residual suppression



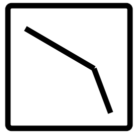
2. Resonance damping:

Control system with disp. sensors



Room-temperature part:

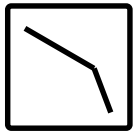
 **DC+Damp**

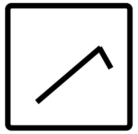
 **DC**

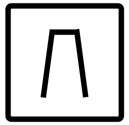
IP / **Vertical filters** / **BF-Yaw**

* Pendulum mode damping
* drift compensation

Cryogenic part:

 **DC**

 **Damp**

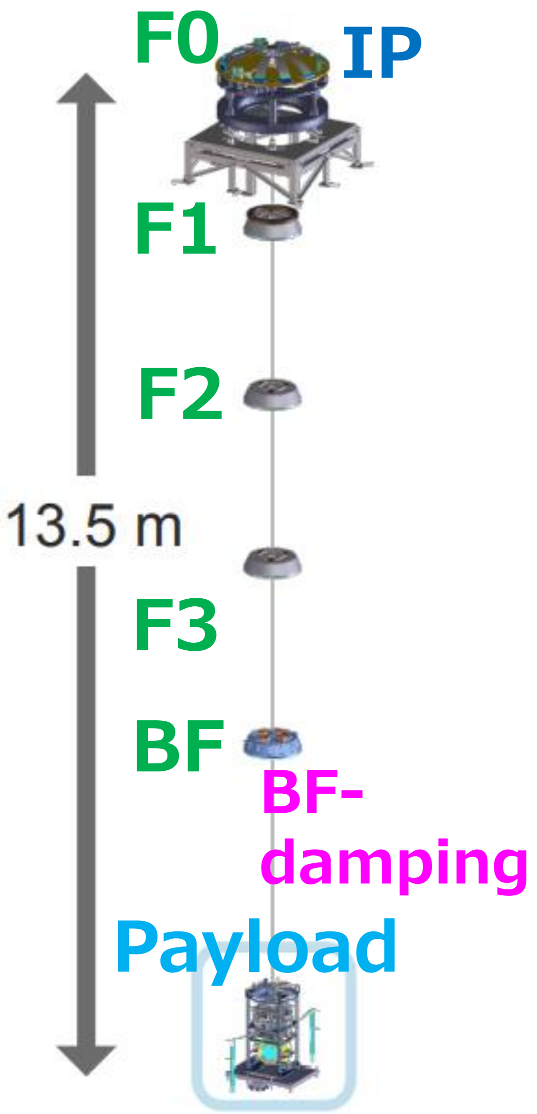
 **Band-pass damping**

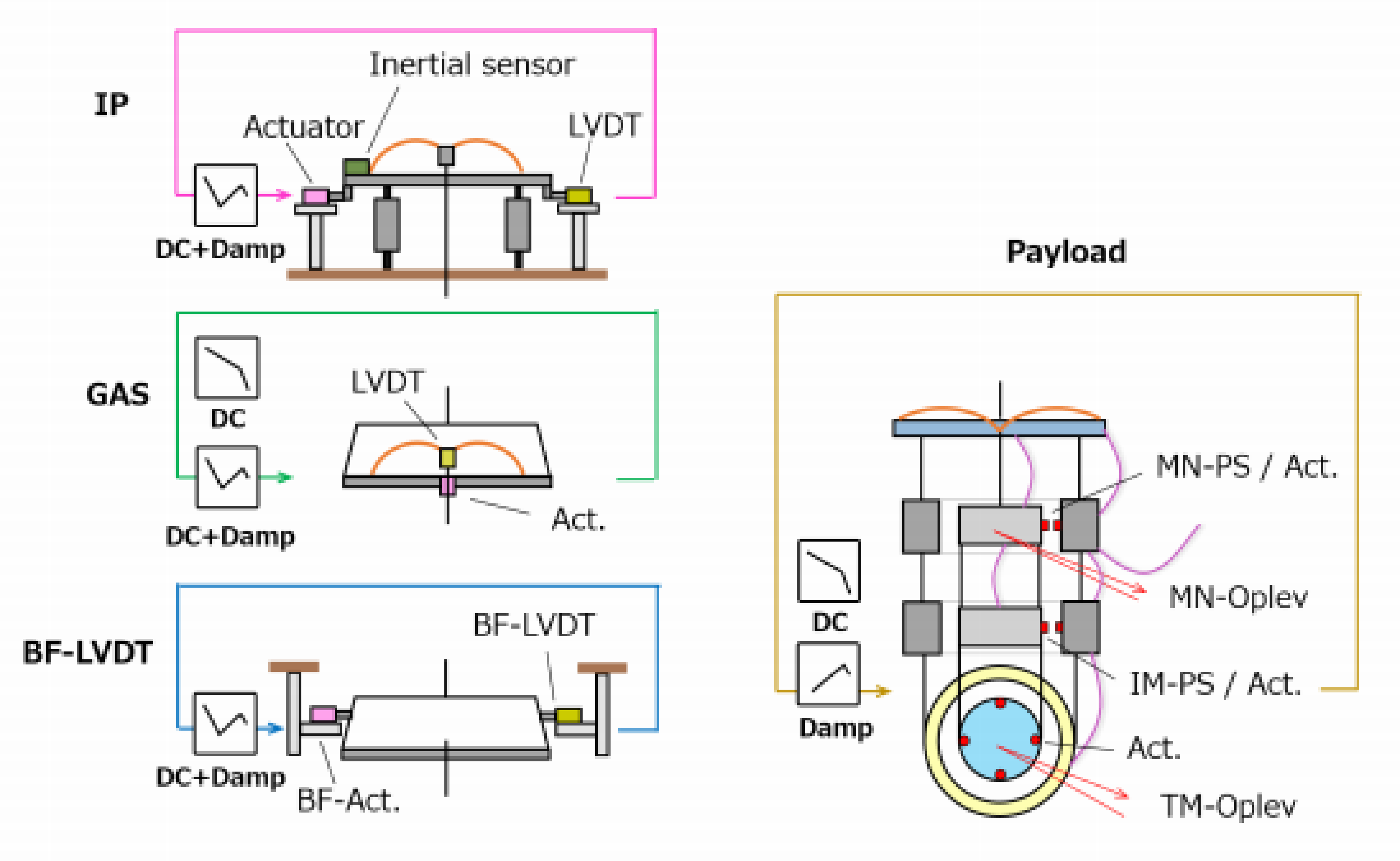
Payload

* Internal mode damping
* Mirror alignment

2. Resonance damping:

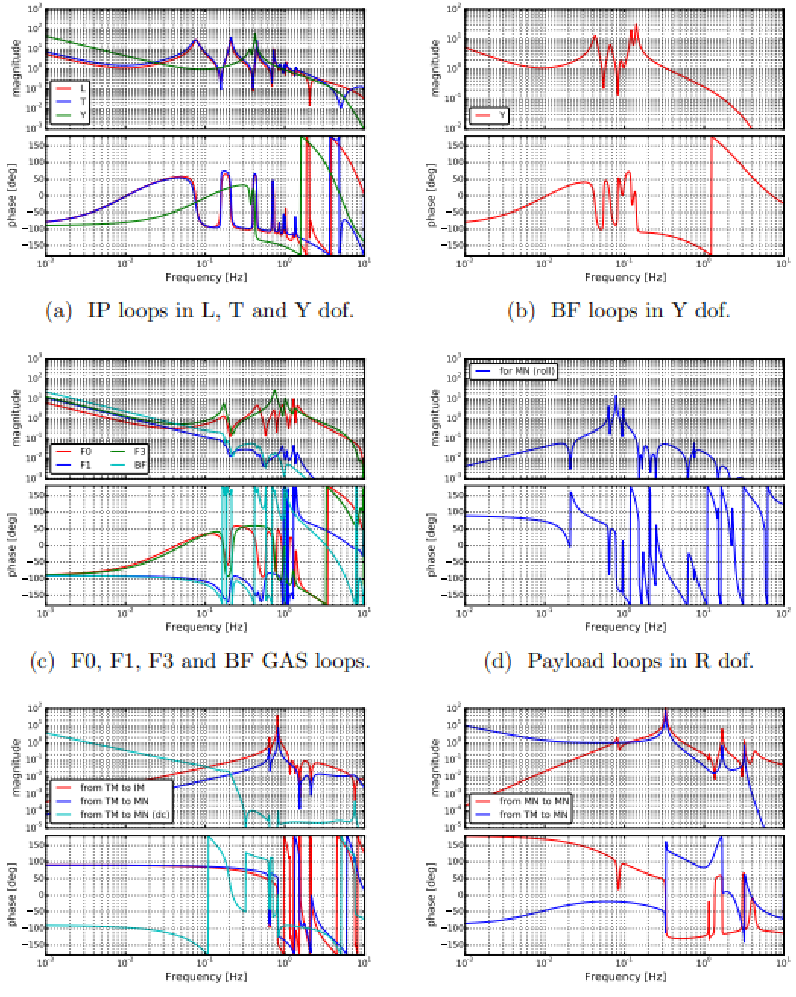
Control system for damping with disp. sensors





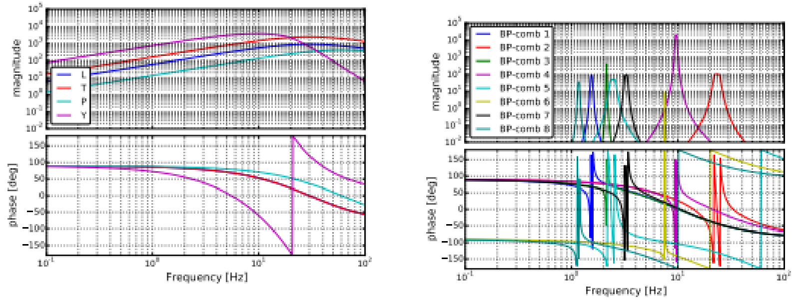
2. Resonance damping:

Open loop transfer functions for Control system for damping with disp. sensors



(a) IP loops in L, T and Y dof.
(b) BF loops in Y dof.
(c) F0, F1, F3 and BF GAS loops.
(d) Payload loops in R dof.
(e) Payload loops in P dof.
(f) Payload loops in Y dof.

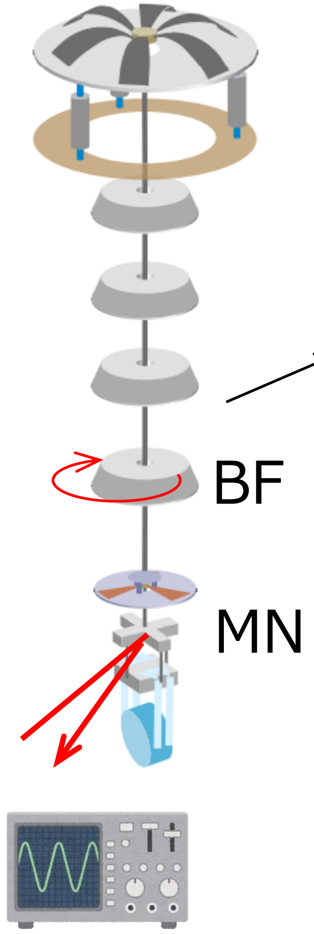
Figure 6.12: Open loop transfer functions of the implemented servo filters for the calm-down phase.

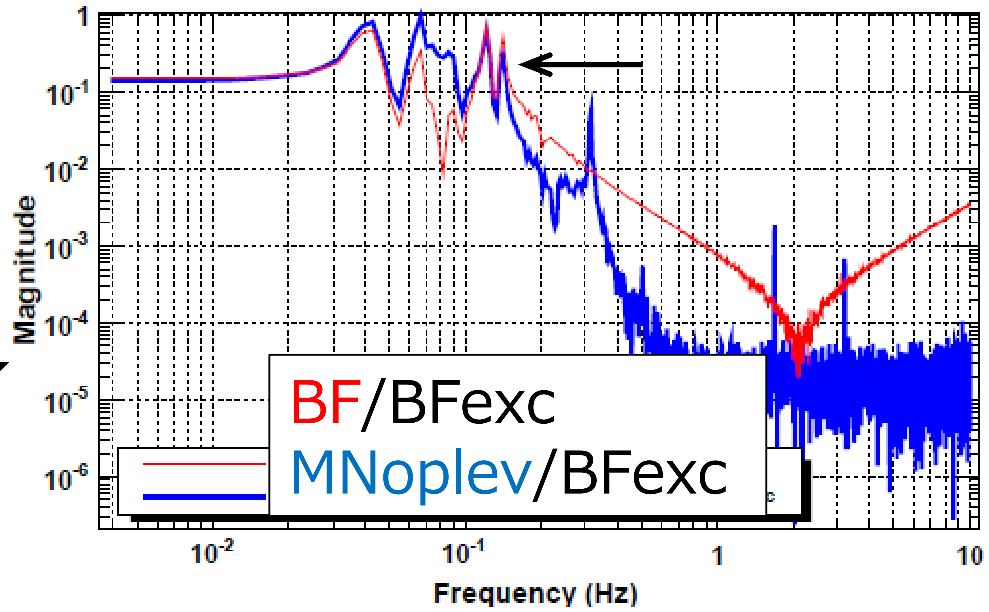


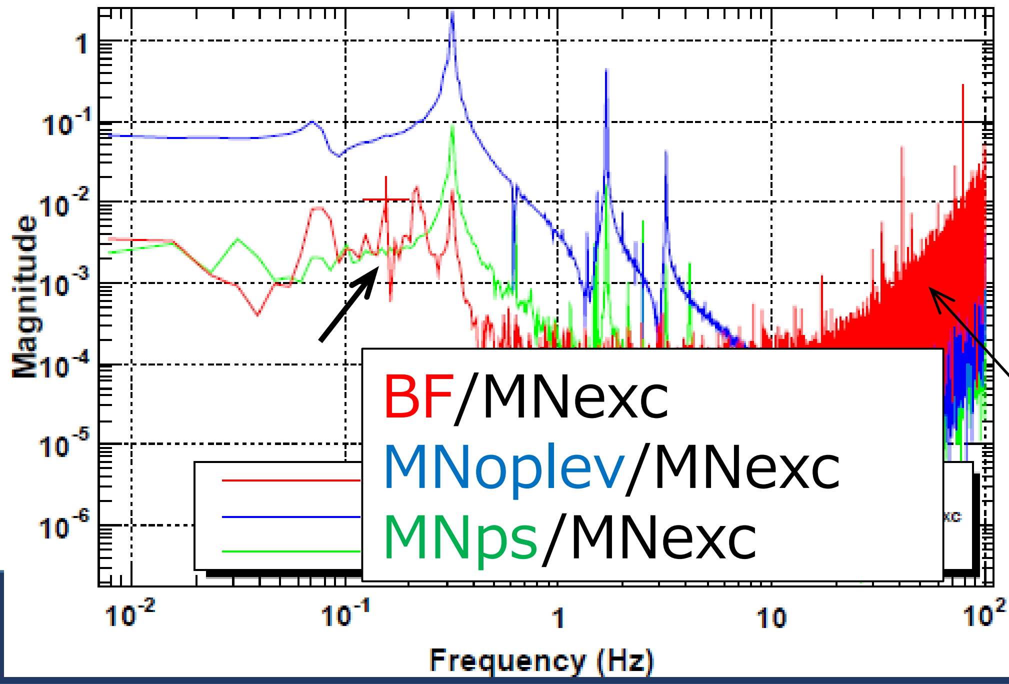
(a) PS loop filters at MN-stage in L, T, P and Y dof.
(b) Implemented band-pass comb filters.

Figure 6.13: Implemented servo filters in addition to the ones in Table 6.1.

So, is this unknown Yaw mode problematic for the target?

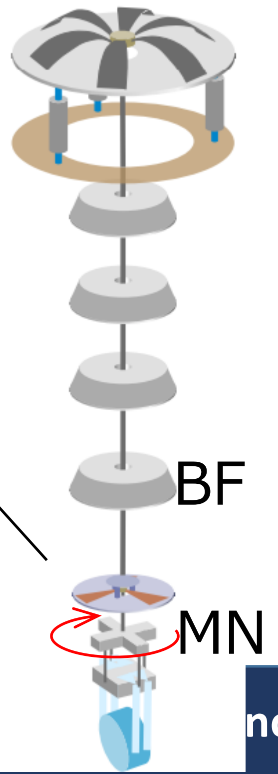






→ No for now, at leaset.
for (current) lock-recovery.

* When noise injected at **BF**-stage:
  → The mode looks exited.



* When noise injected at **MN**-stage:
  → Not (clearly) exited in TM-chain.

* The decay time ~3min.

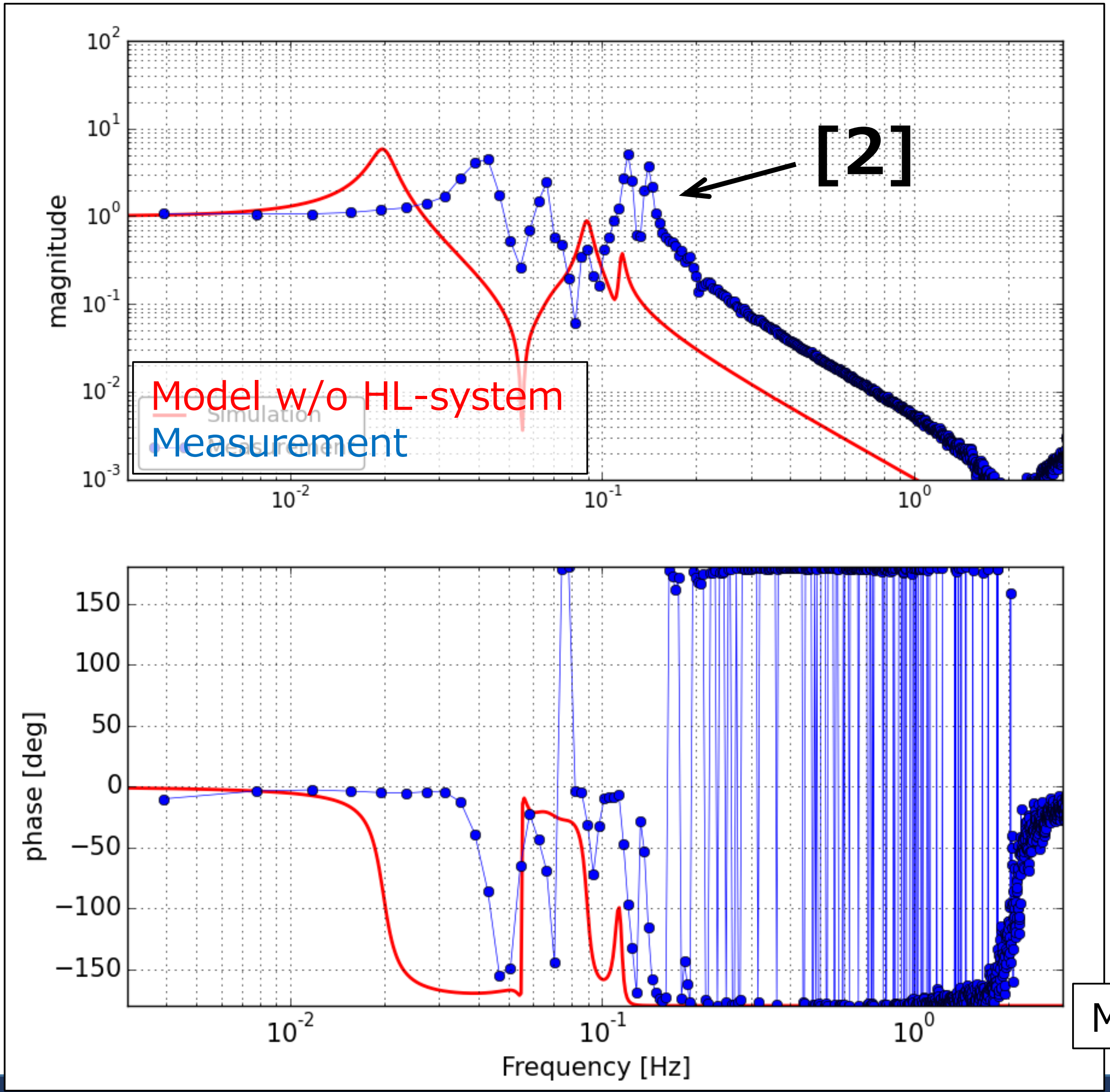
Summary of this work:

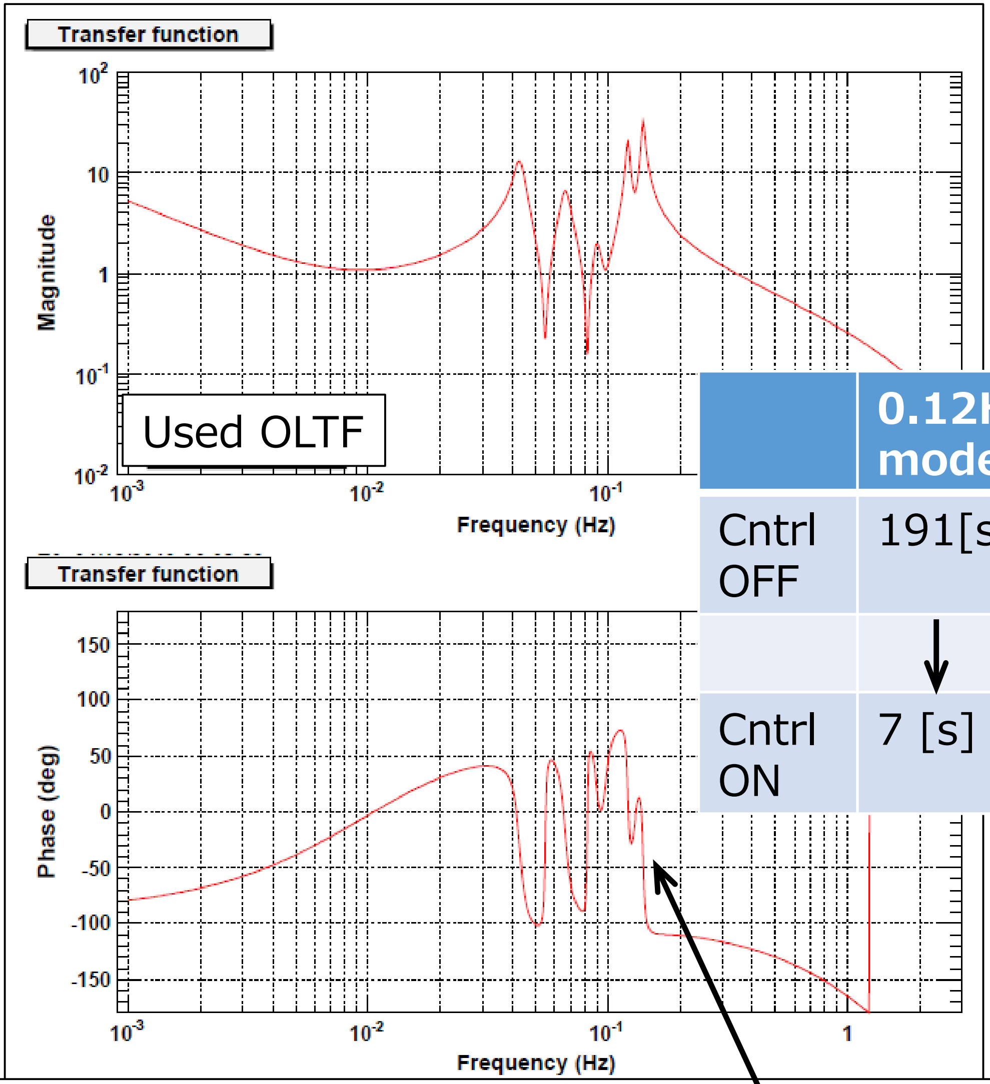
-- The installed damping control system damped all the resonances which disturbs the lock acquisition **for the lock-recovery mode**.

-- exception: one mode
  -- This mode looks from HL-system
  -- This would be problematic when upper stages are used for the global controls. → Further improvement

-- In this work, the payload damping system is constructed mainly with the optical levers (relatively small linear range).
  -- better to utilize Photo-sensors more effectively.

unknown Yaw mode [2]?

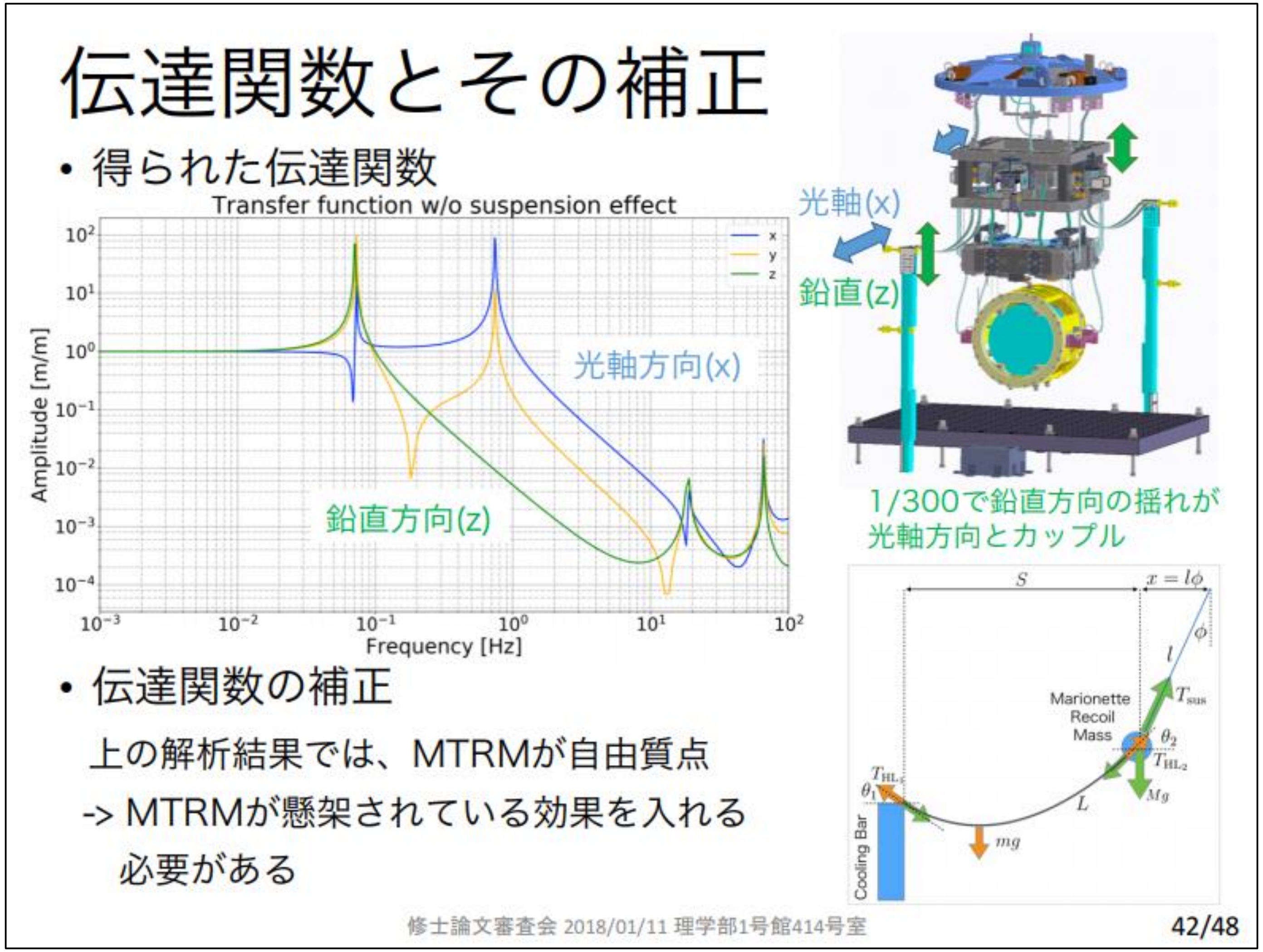




	0.12Hz mode	0.14Hz mode
Cntrl OFF	191[s]	330 [s]
	↓	↓
Cntrl ON	7 [s]	180 [s]

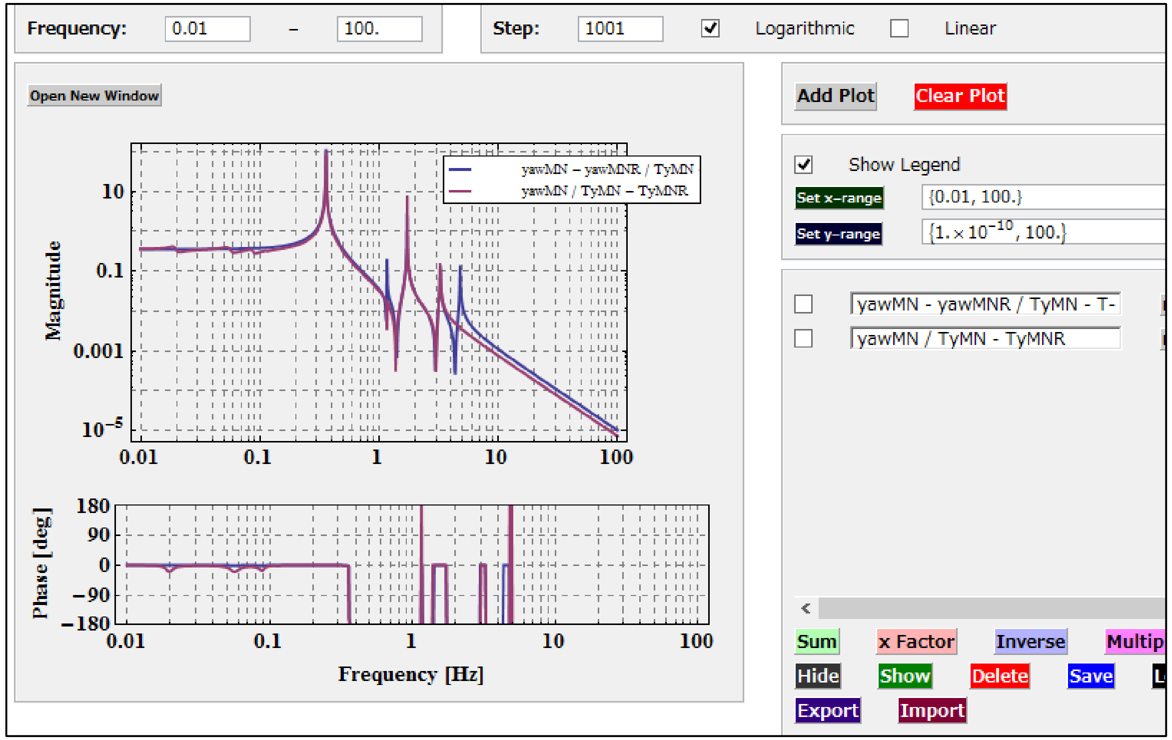
More finely tuned phase compensation might work

Expected heat link frequency response



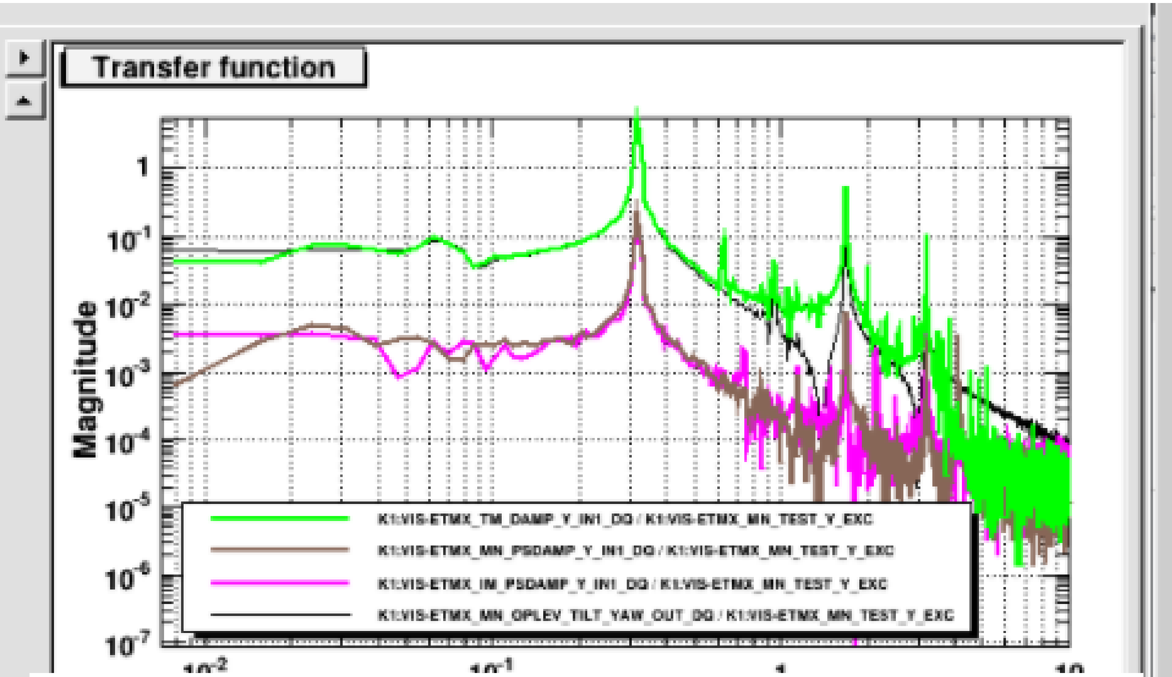
JGW-P1807766

Photo-sensor inter-calibration



* According to a simulation, the following force TFs should have same DC gain (since RM-chain is still enough compared to TM-chain it seemed).

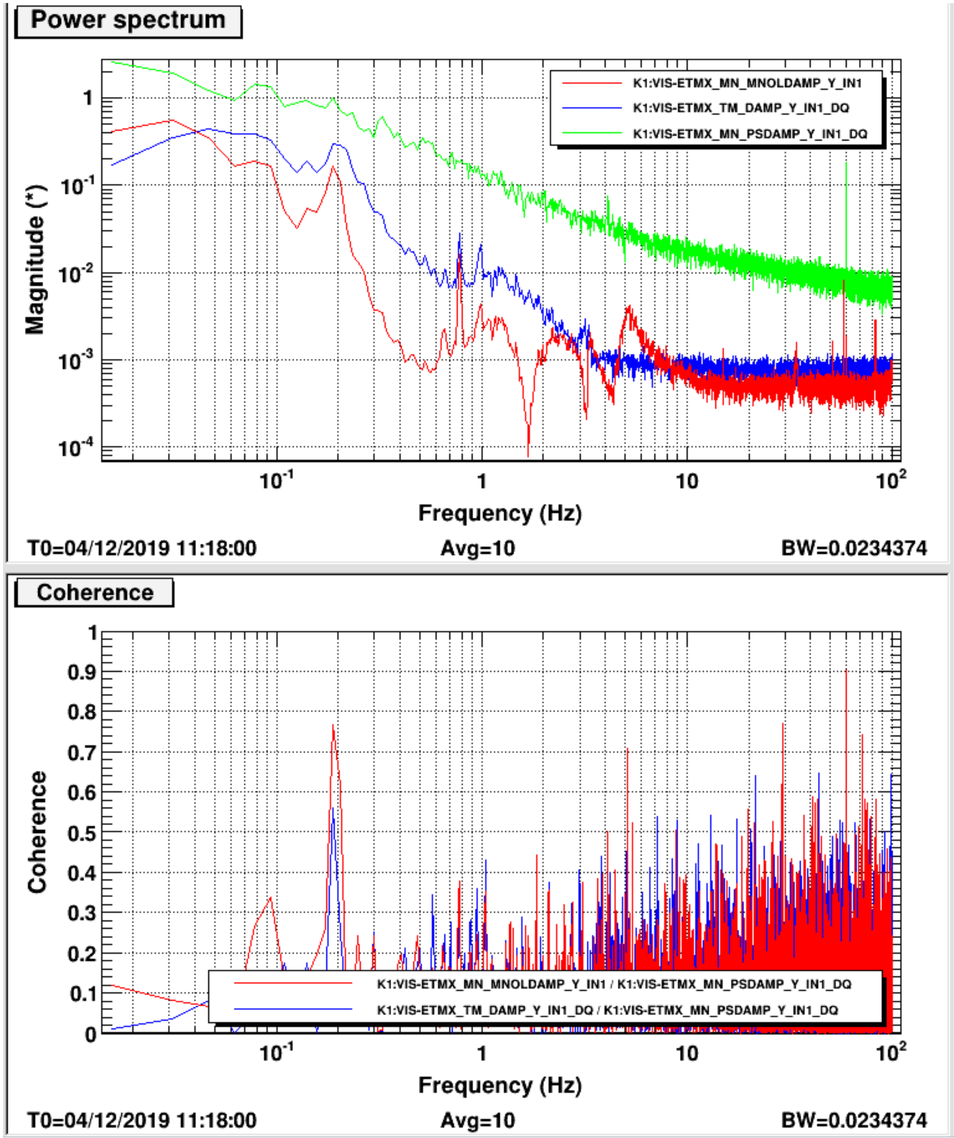
MN(Y)ps/MN(Y)exc and
MN(Y)oplev/MN(Y)exc



(current PSDAMP_IN) * ~20 → urad

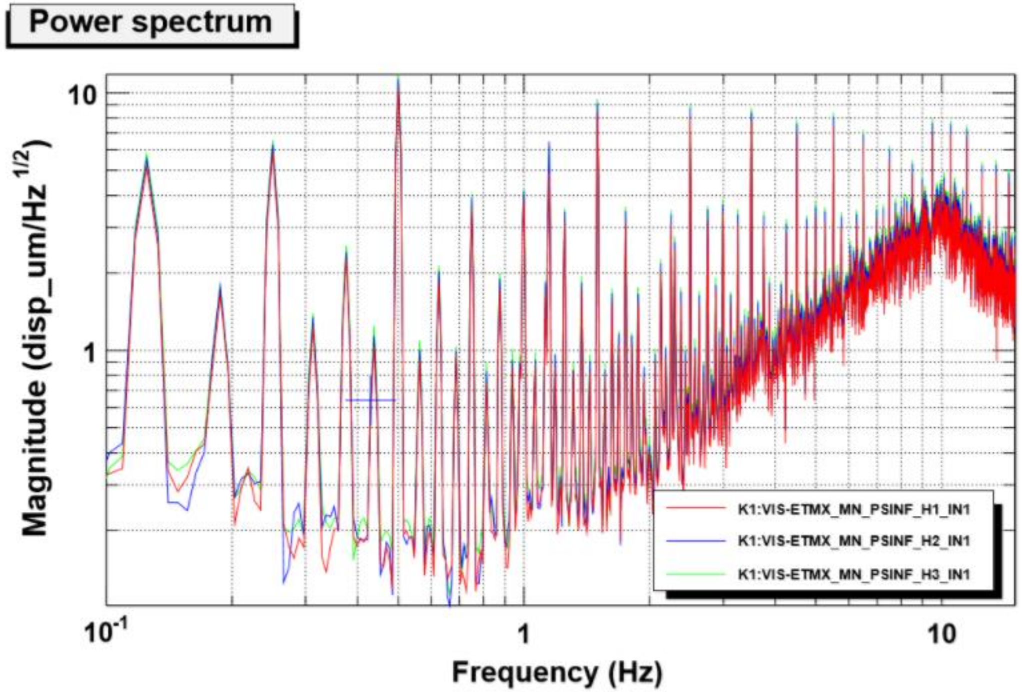
Photo-sensor inter-calibration

[urad/rtHz]



* Spectra w/ the calibration factor.
* Might be too large (a bit) though, direction looks okay.

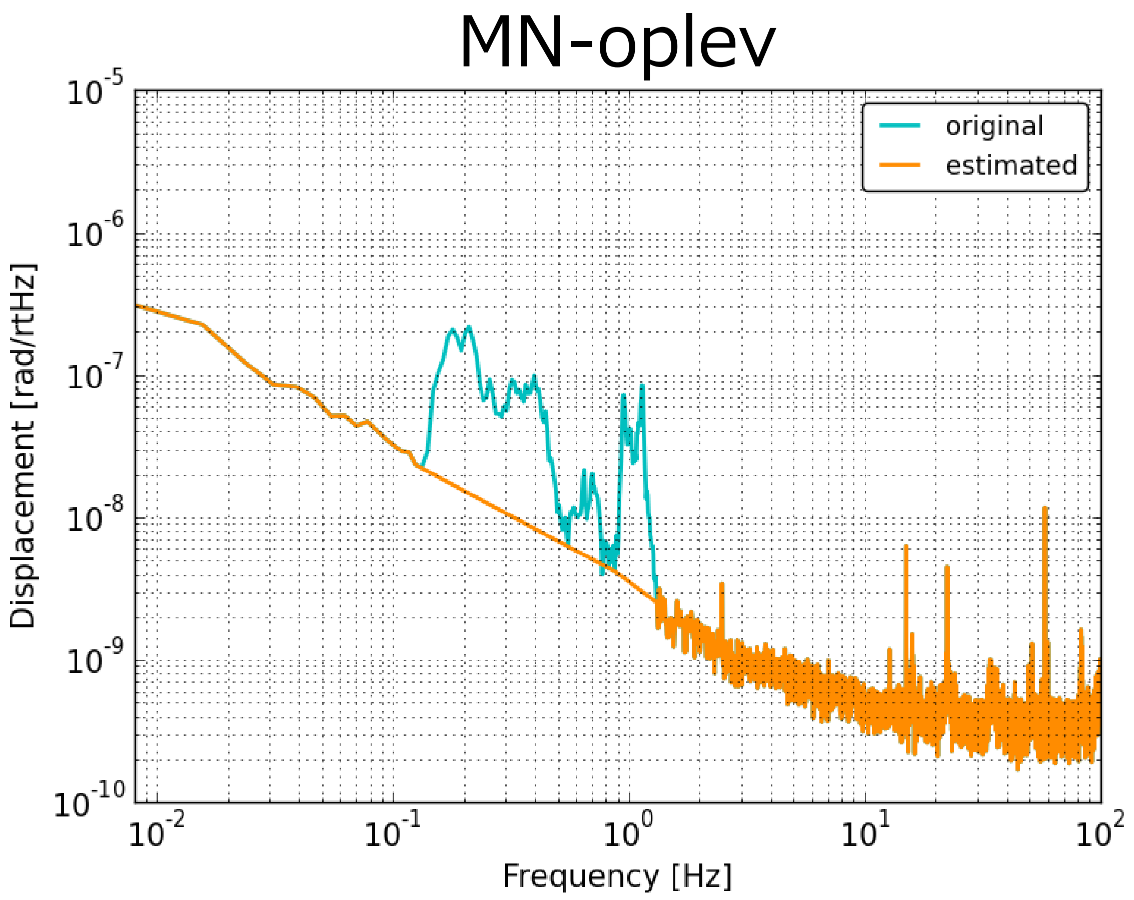
Roughly estimated

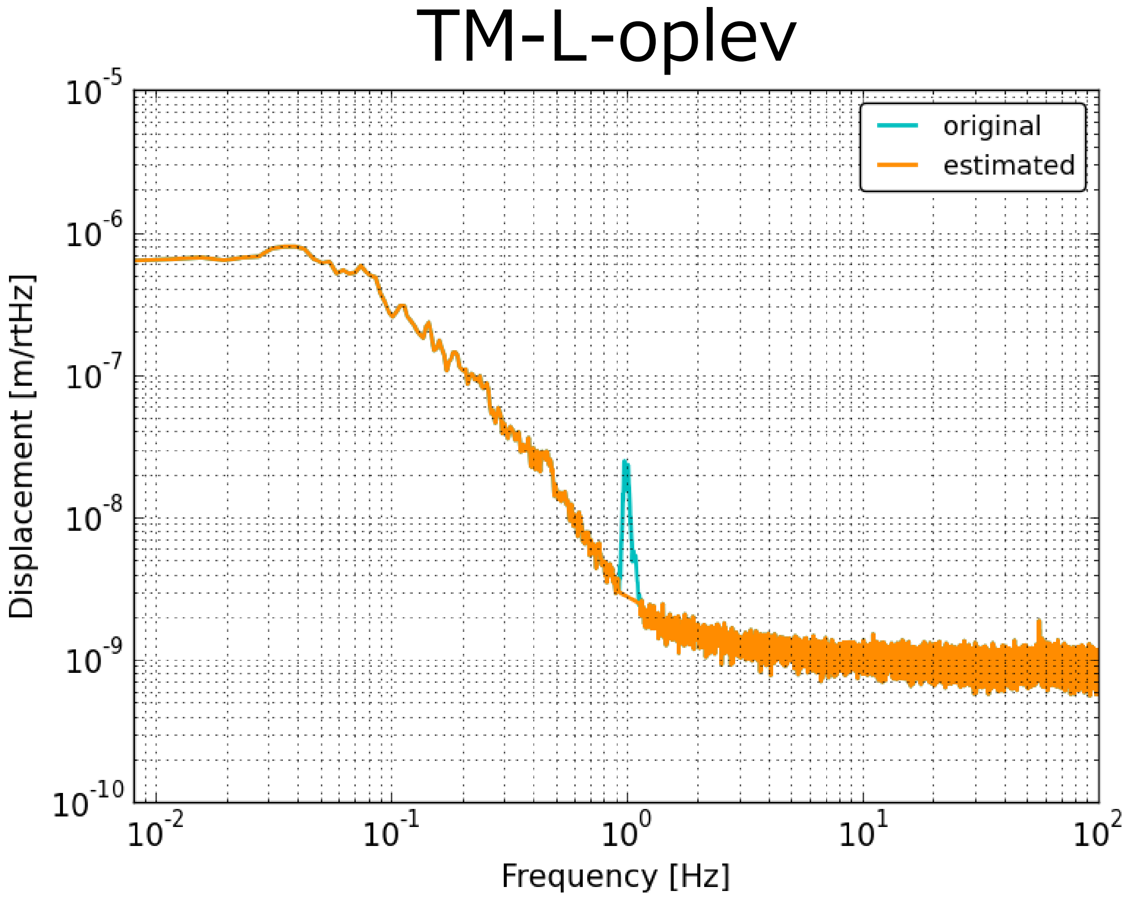


* We have to keep in mind that the PS in ETMX becomes sometimes crazy though.

Optical lever noise floor:

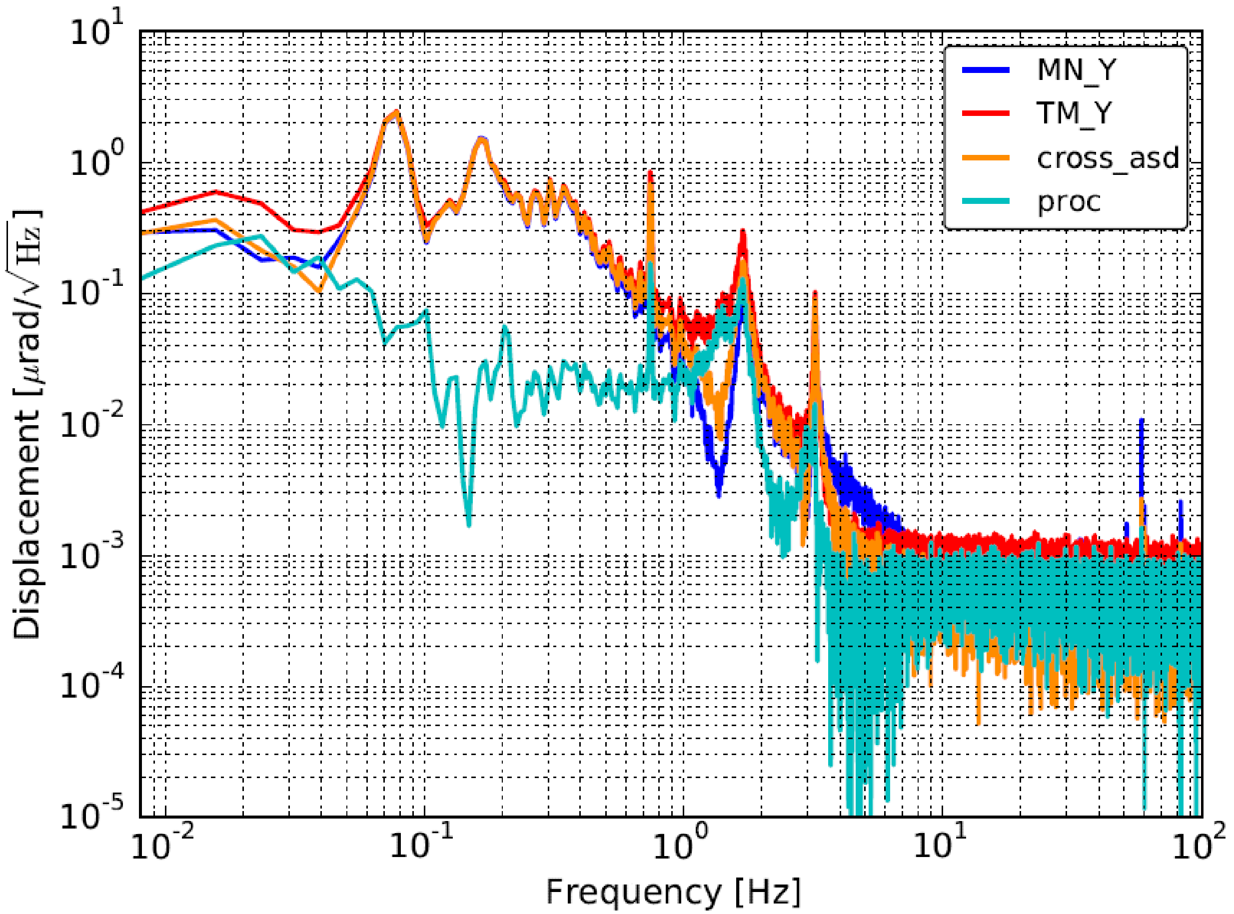
* Obtained with interpolation: (~~Estimated~~ → interpolated)





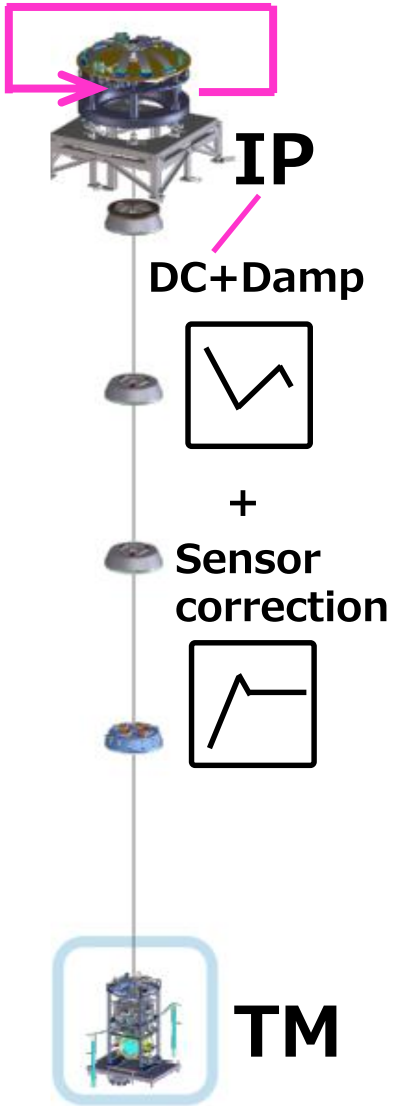
Optical lever noise floor:

* Obtained with correlation analysis (TMY_ASD – MNY_cross_ASD):

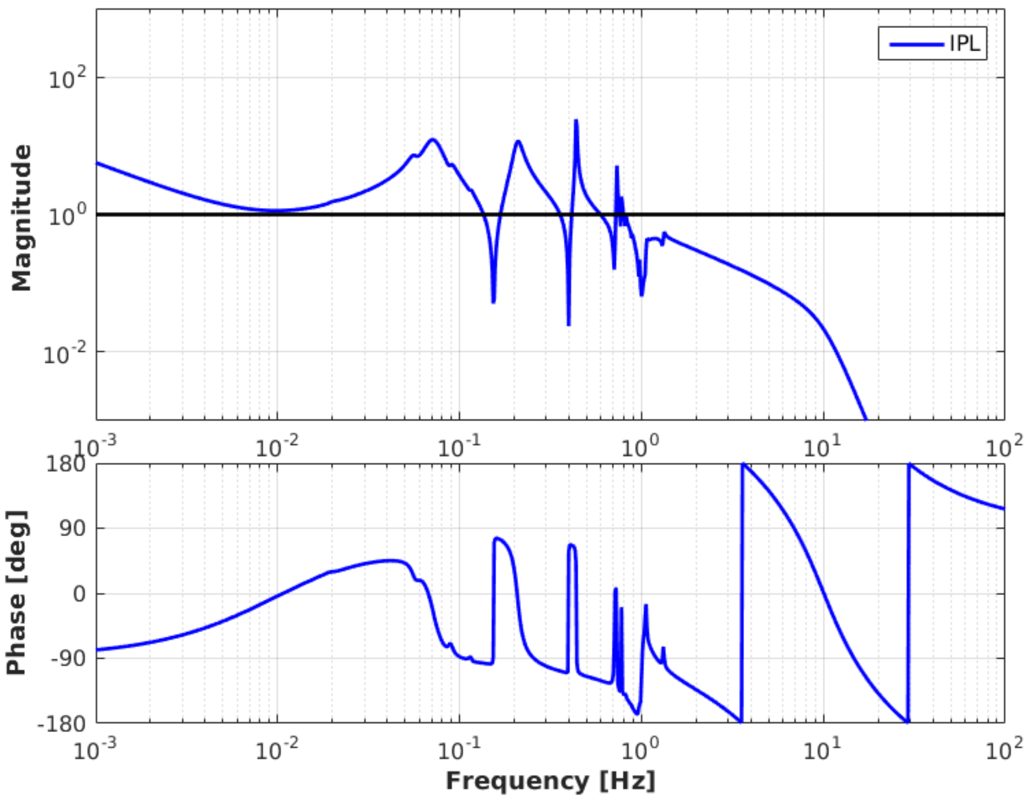


Notes: RMS suppression

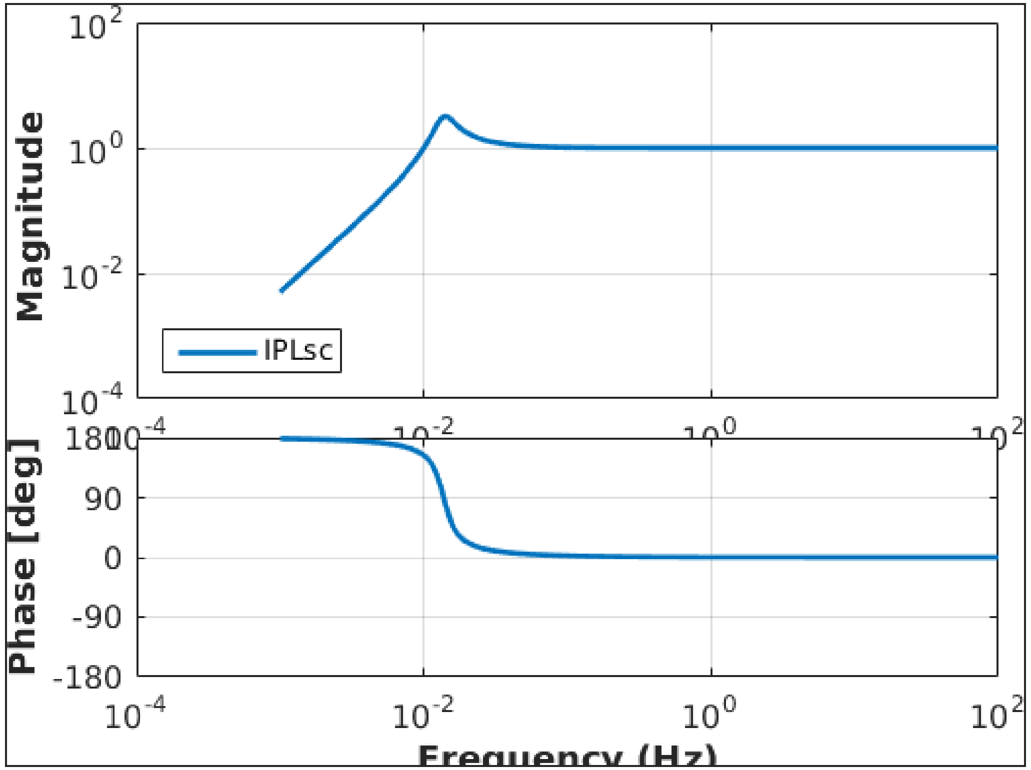
制御ループ at IP-stage:



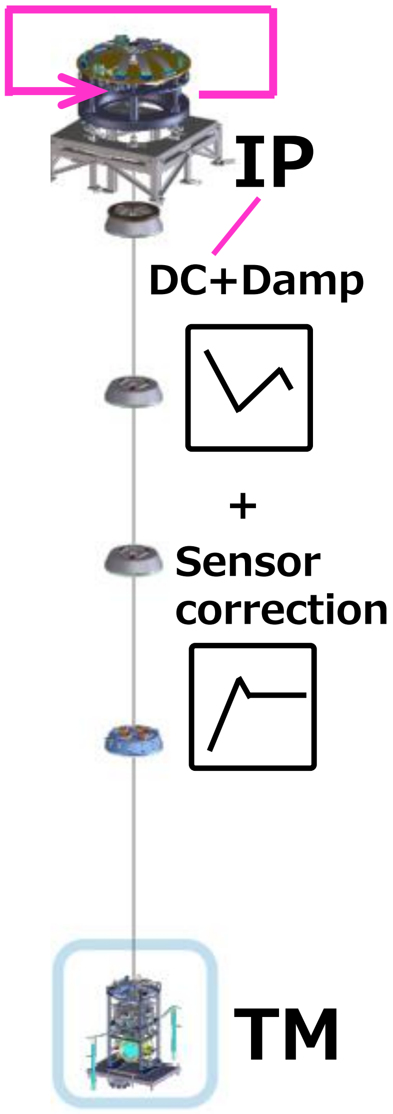
1. OLTF for IP-LVDT

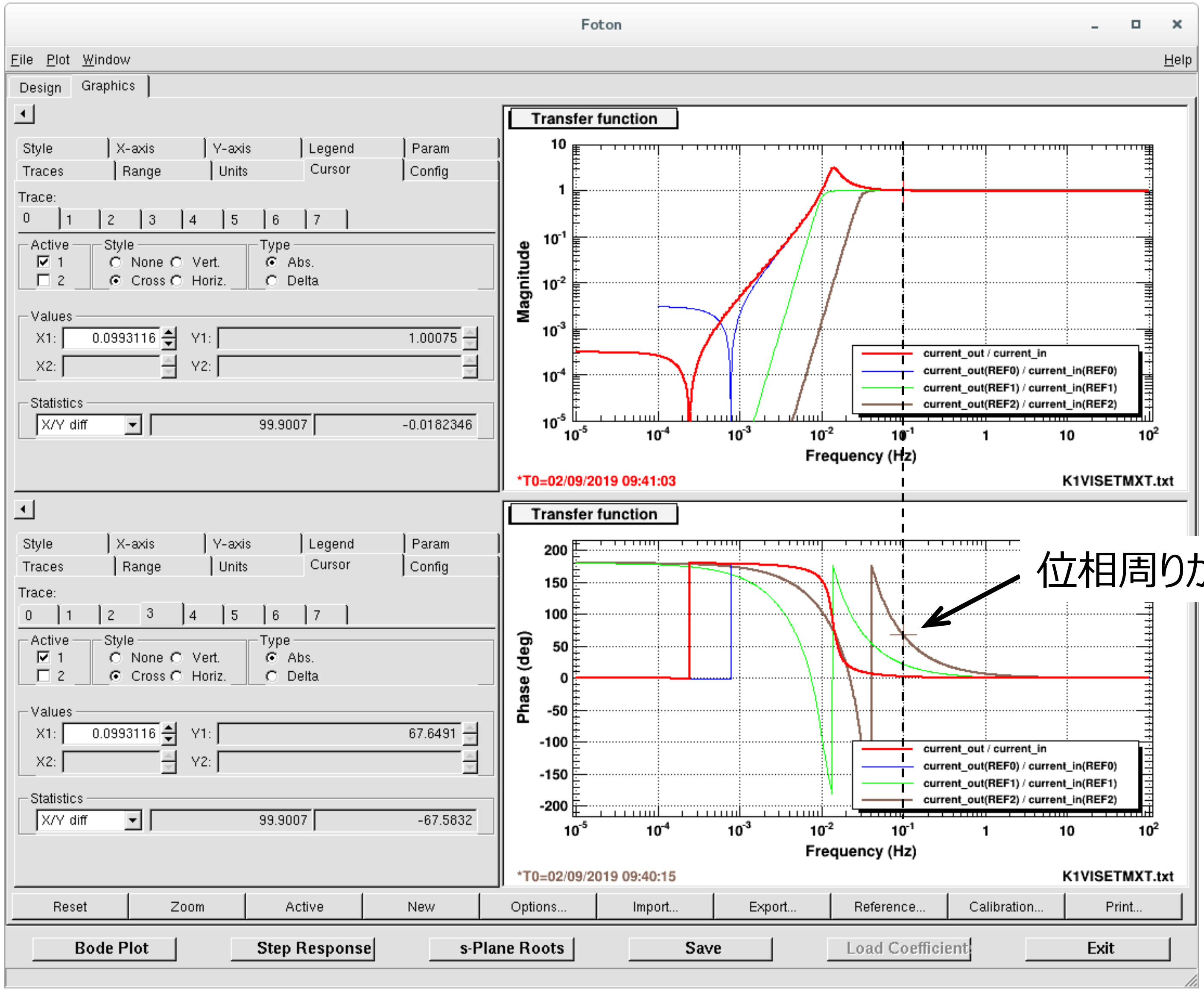


2. Sensor correction filter



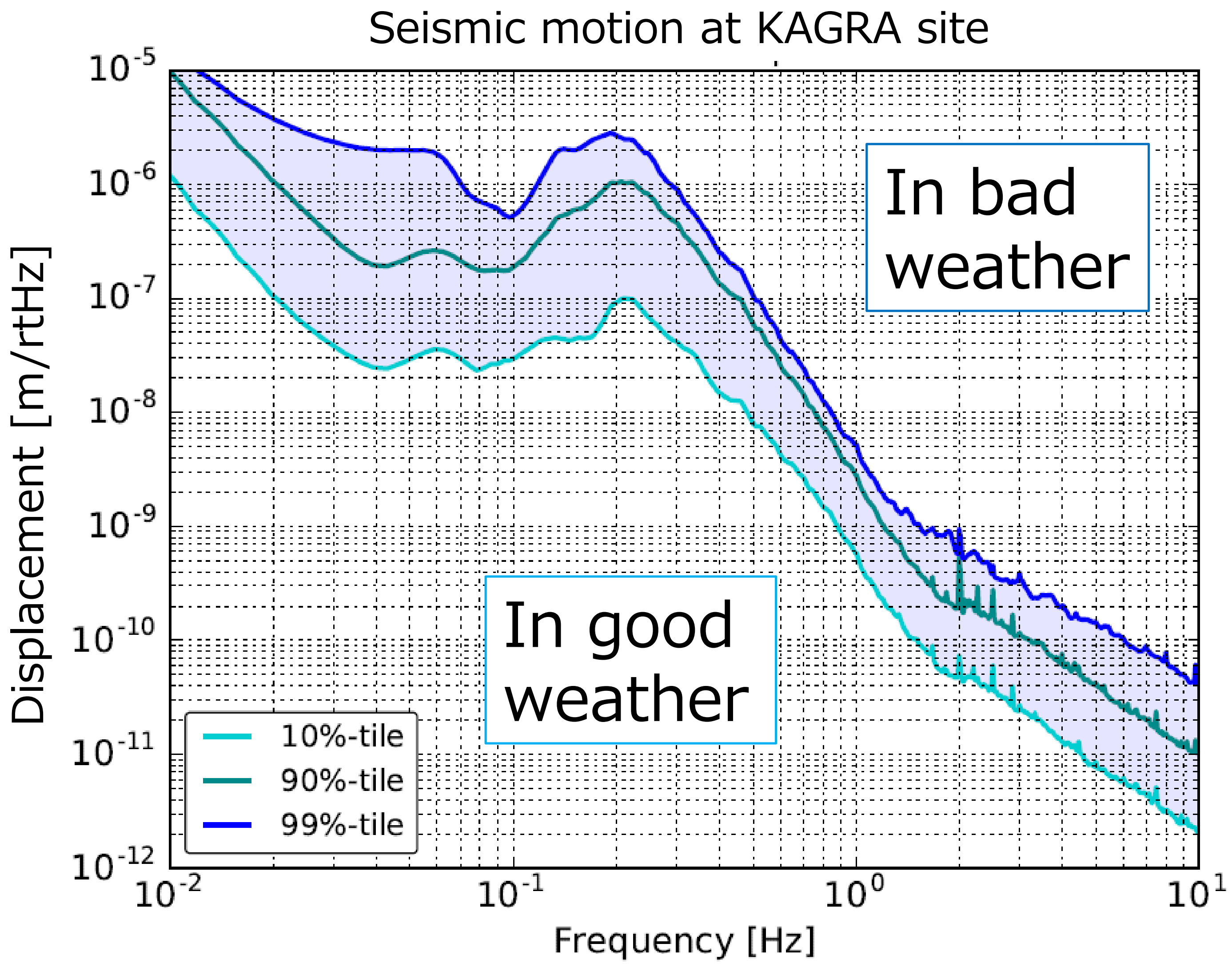
Sensor correction filter の検討





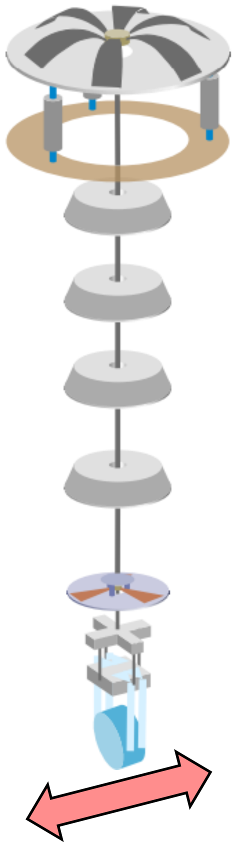
位相周りがなるべく少ないものを採用した。

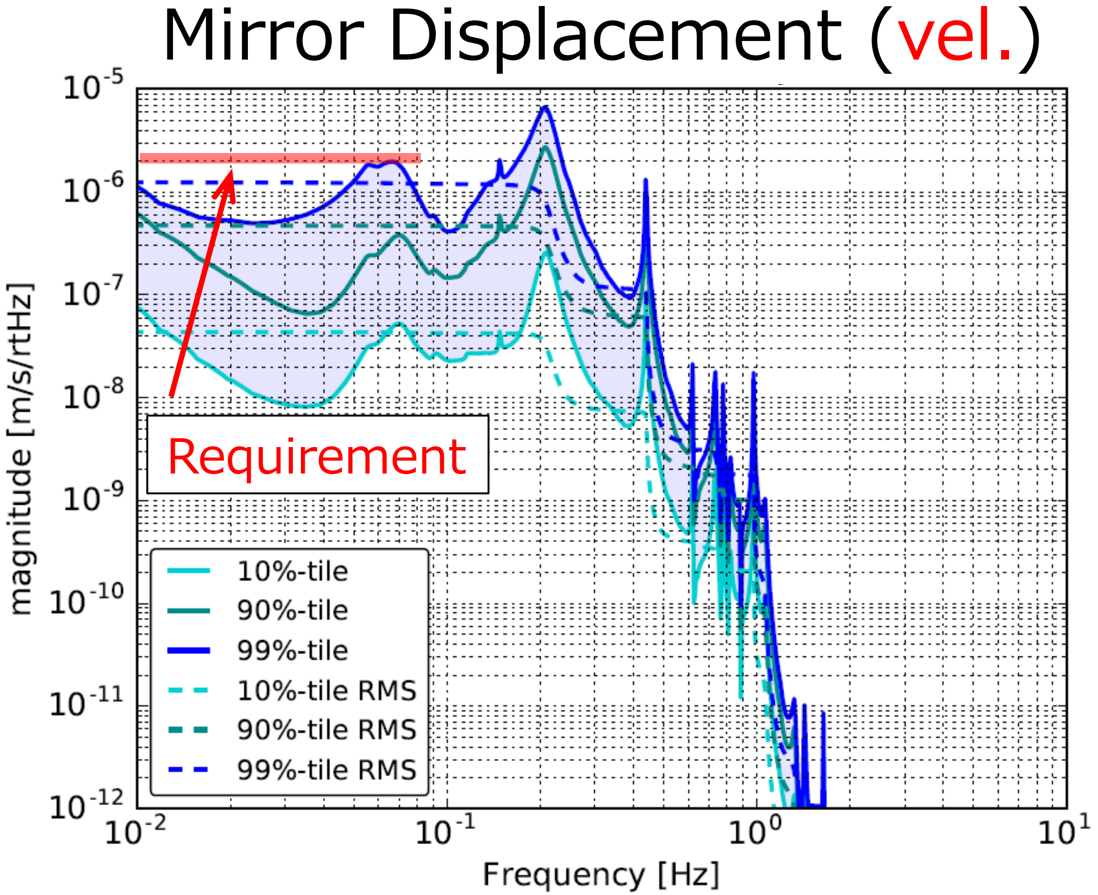
Ground motion at KAGRA site

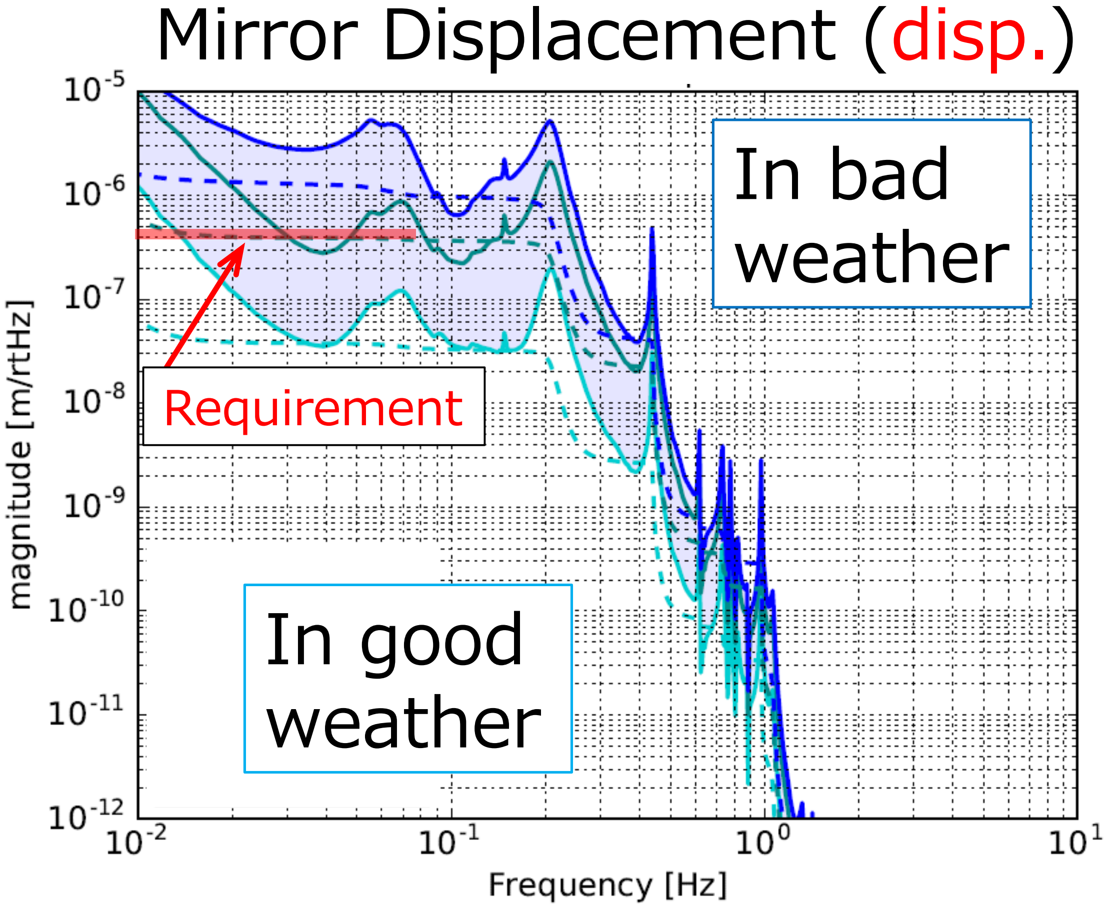


Suspension response at KAGRA site w/o control

* Simulated mirror residual motion:

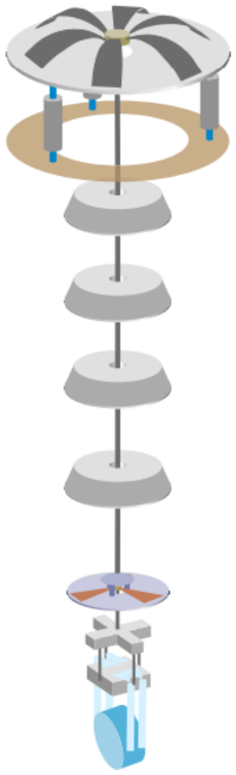






Ref: https://gwdoc.icrr.u-tokyo.ac.jp/cgi-bin/private/DocDB/ShowDocument?docid=10436

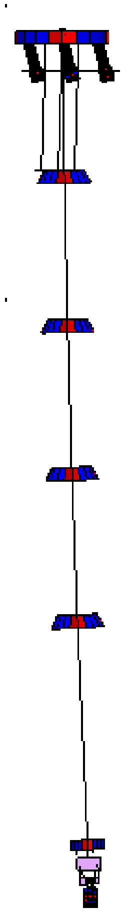
Suspension response at KAGRA site w/o control



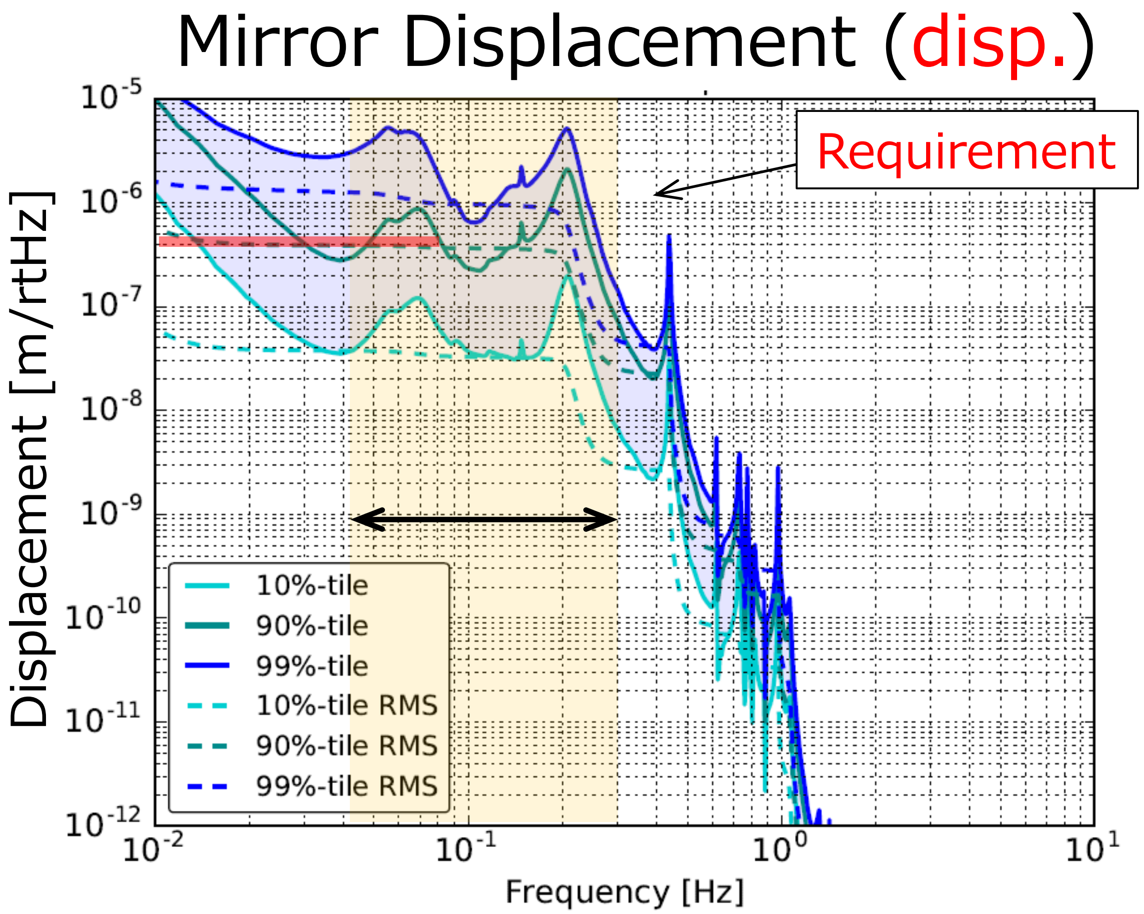
* In good weather
  → req. will be satisfied.

* In bad weather (especially in winter)
  → req. will not be satisfied

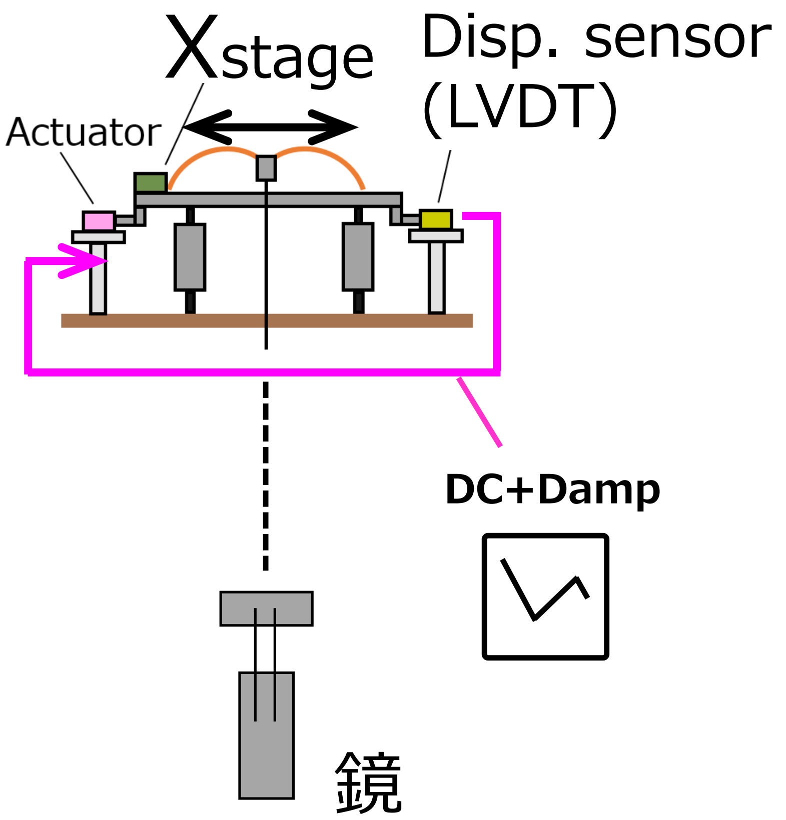
* Contribution to RMS is large in the band.
  → To be suppressed
    → at upper stage.

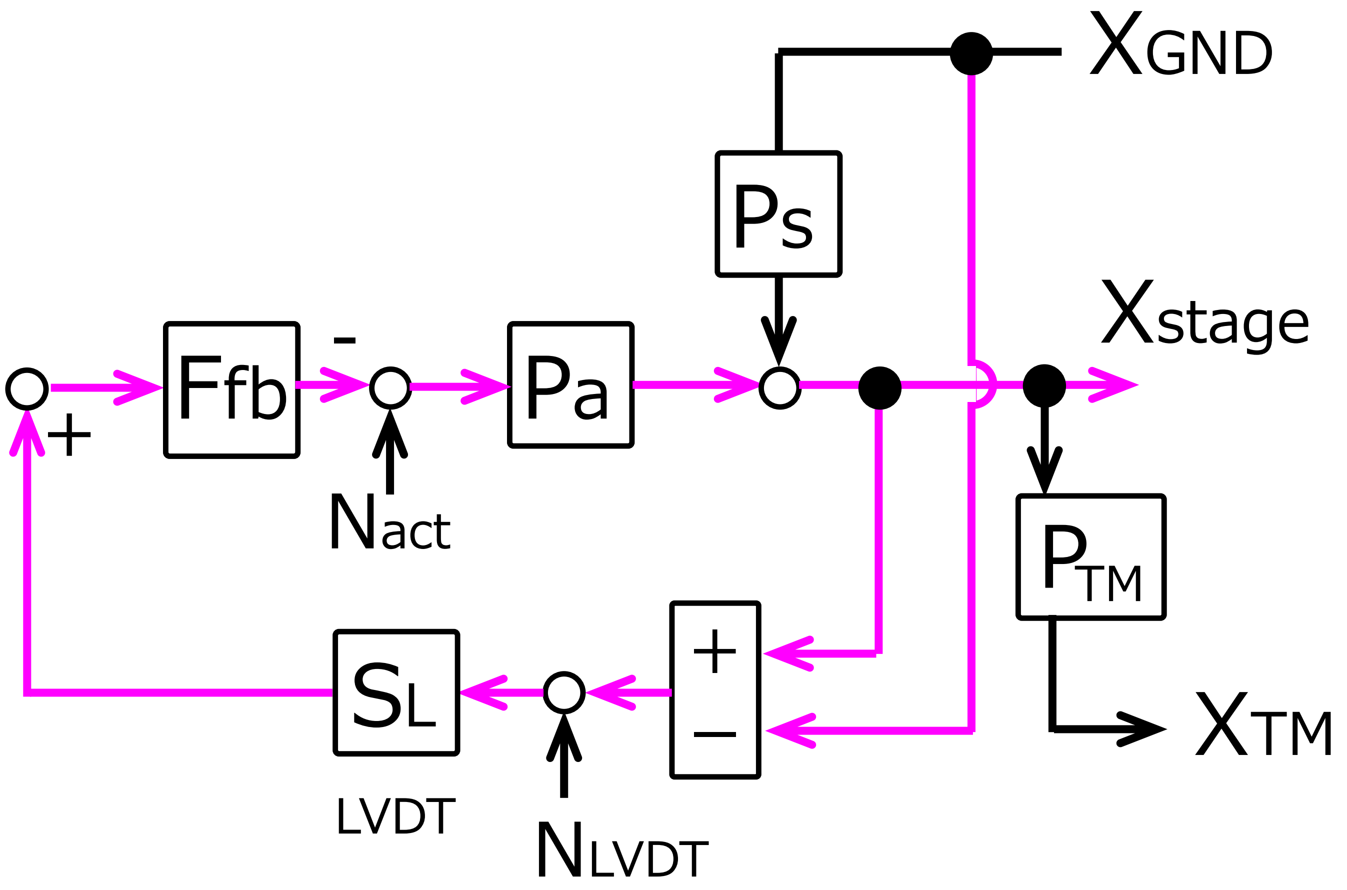


0.2 Hz mode



Control overview (in L):

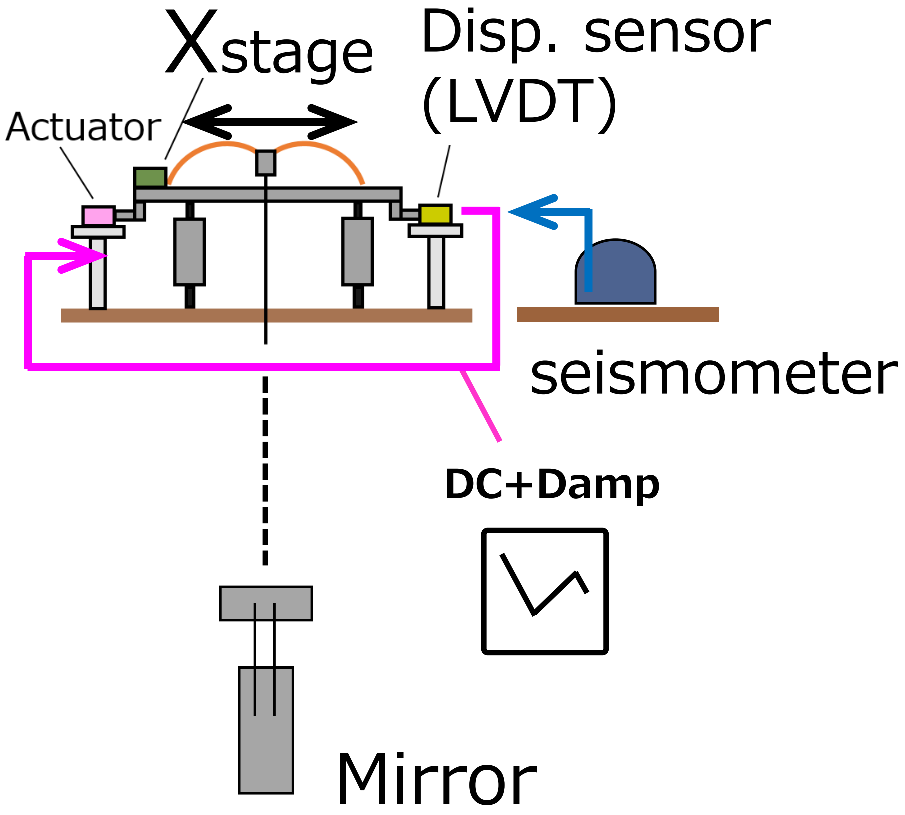


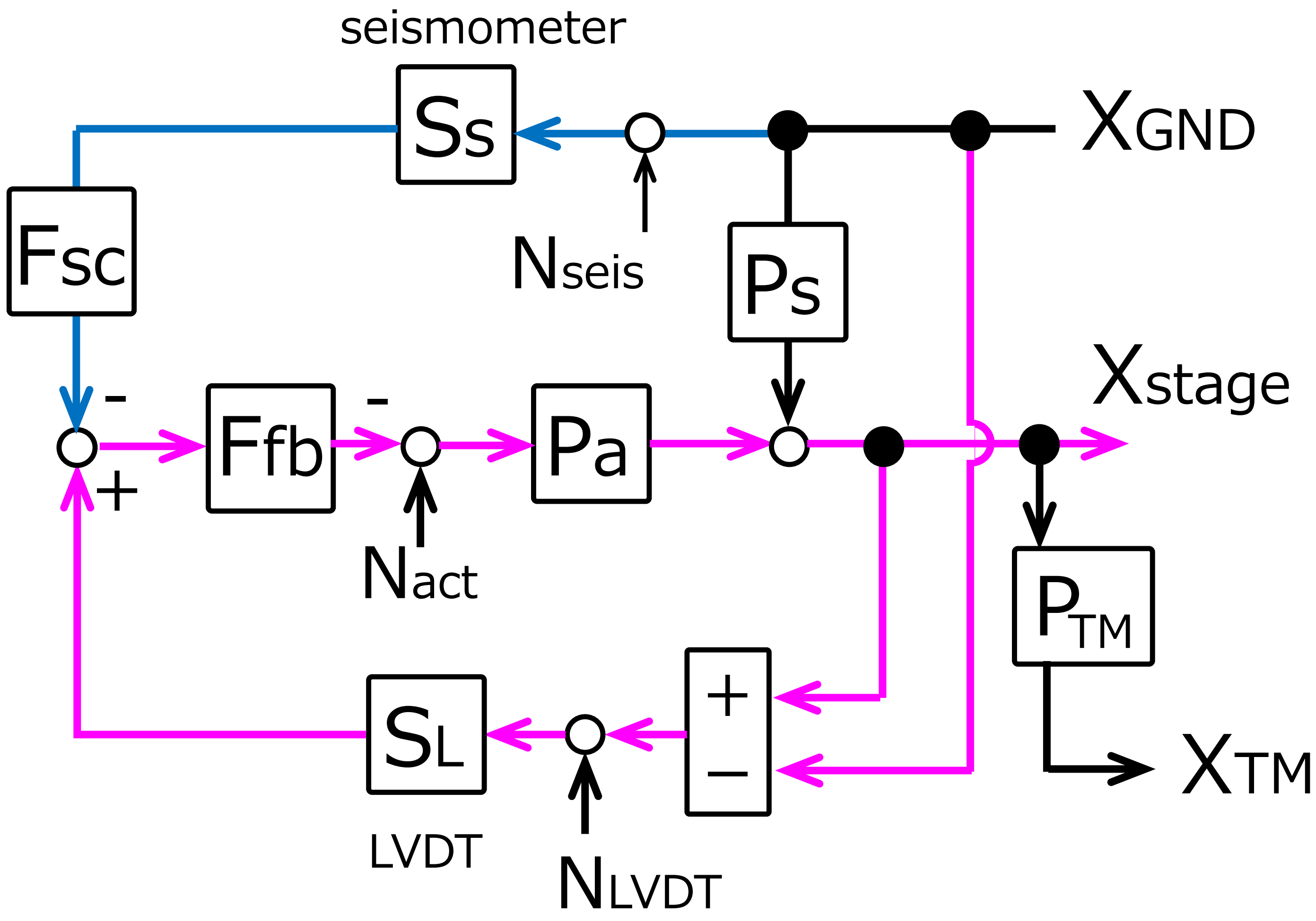


Disp. sensor uses:

(Xstage − XGND) ⟶ Xstage ~ XGND

Control overview (in L):

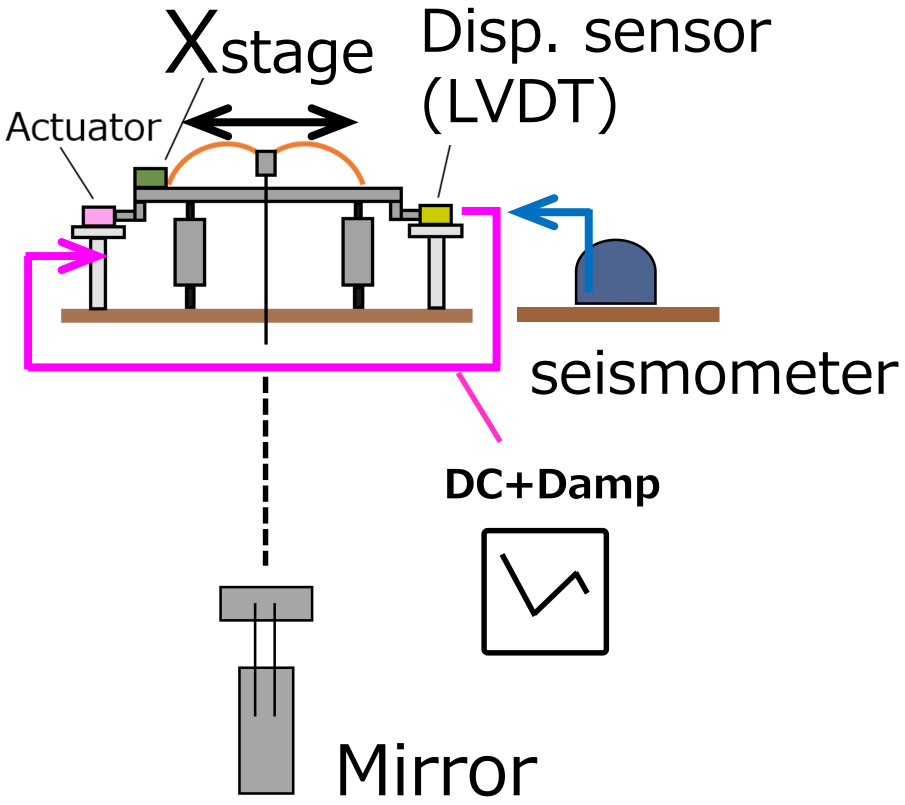


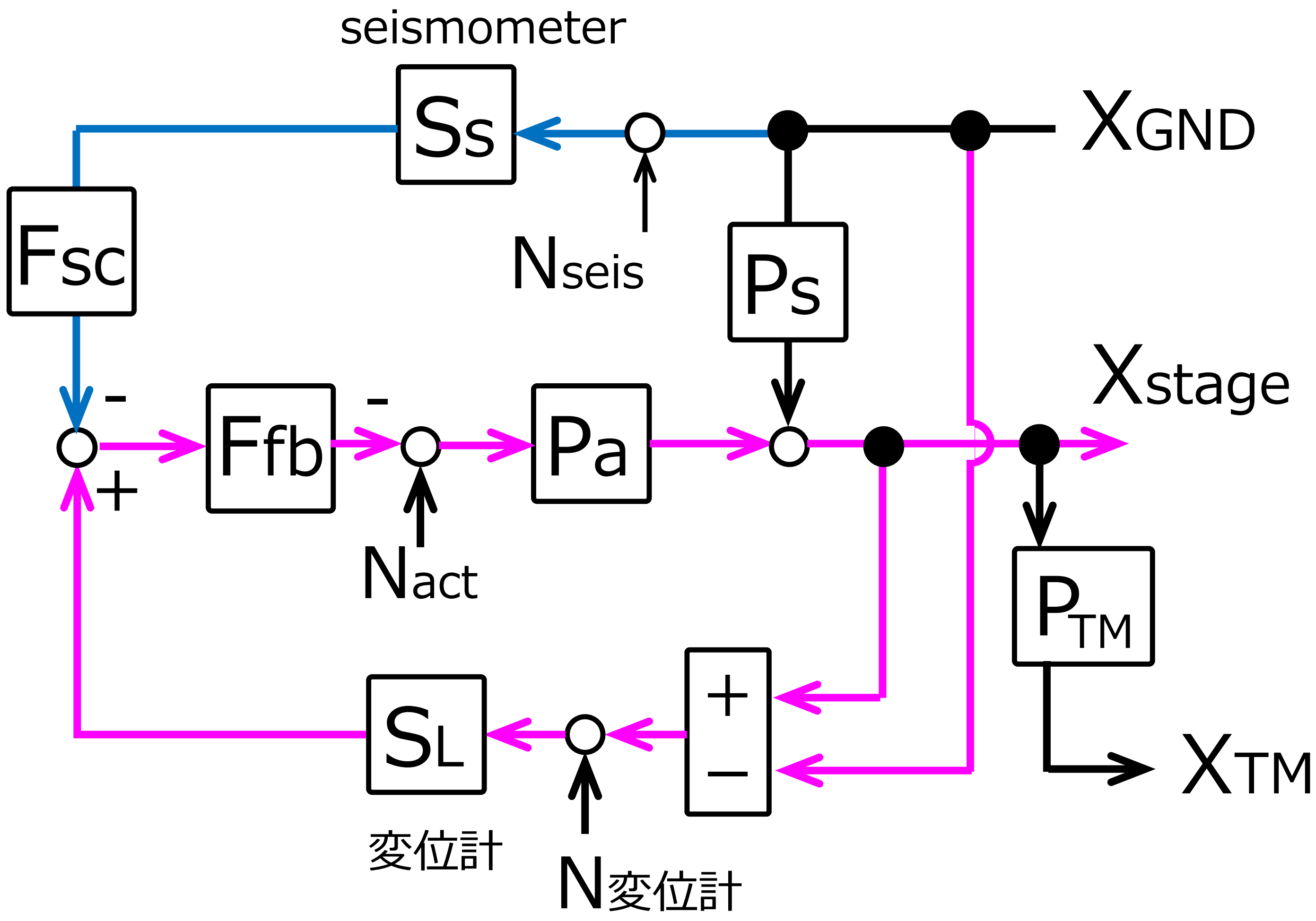


$$X_{stage} = \frac{1}{1+G}\left[G\left(1+F_{sc}\frac{S_S}{S_L}\right)+P_s\right]X_{GND}$$

$$(\, G = P_a\, F_{fb}\, S_L \,)$$

Control overview (in L):



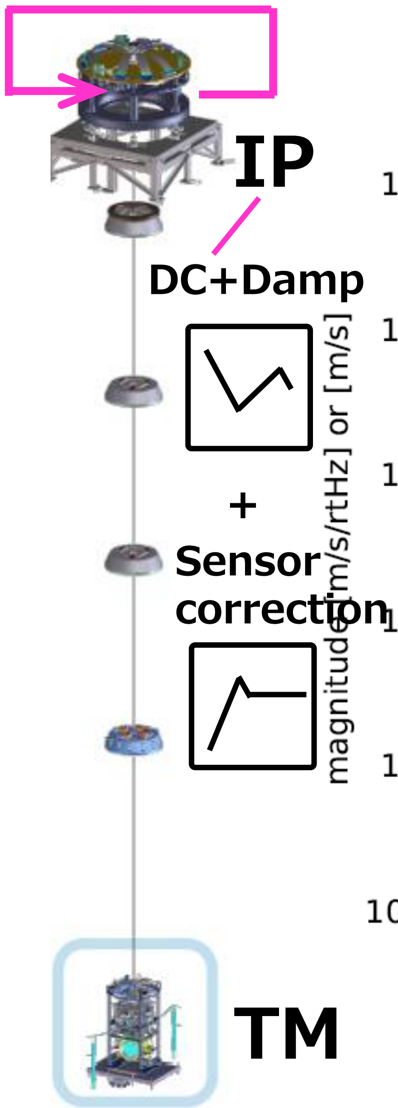


with Fsc = - SL/Ss:

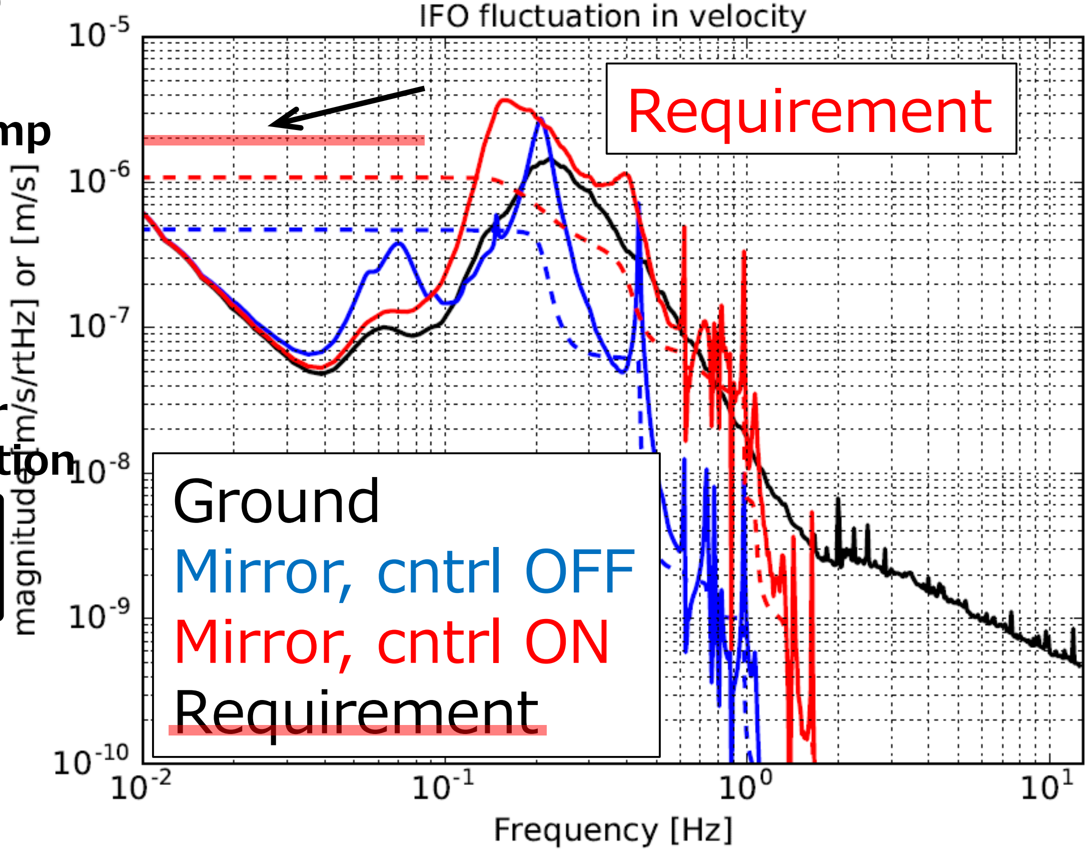
$$X_{stage} = \frac{1}{1+G}\left[G\left(1 + F_{SC}\frac{S_S}{S_L}\right) + P_S\right] X_{GND}$$

Cut the seismic noise injection via LVDT
→ Sensor correction

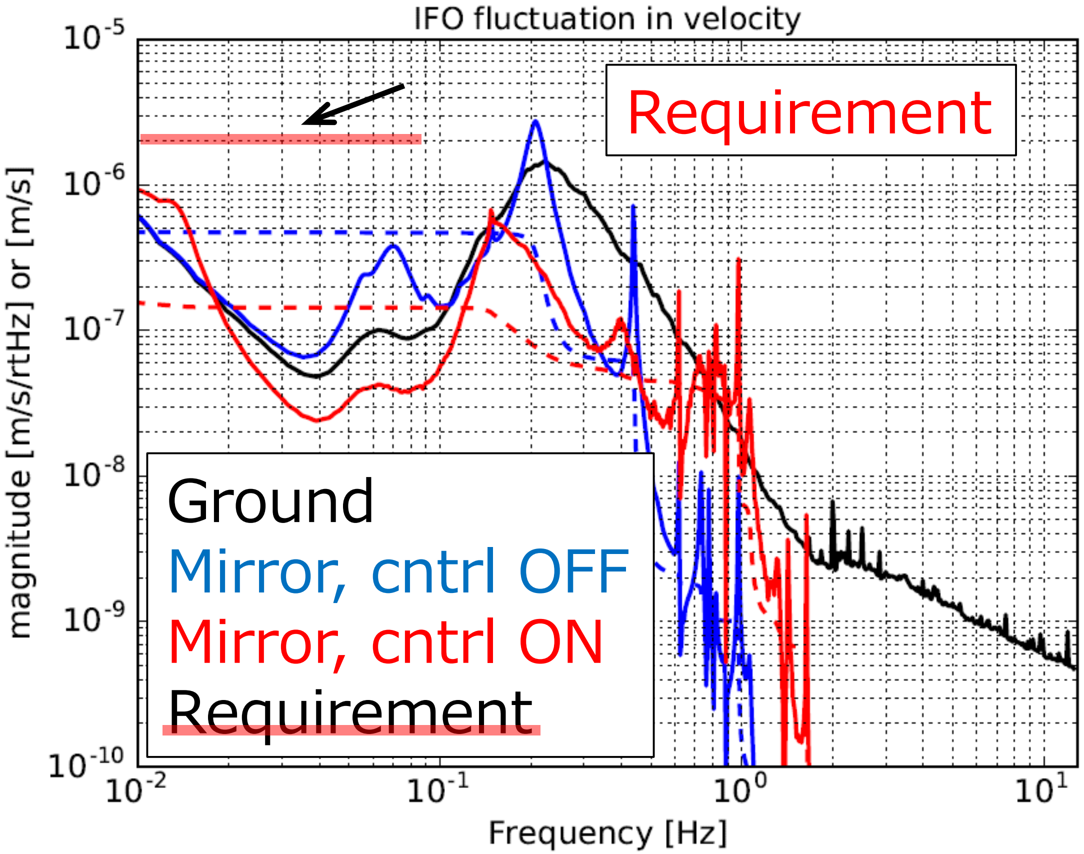
Simulation: mirror velocity w/ 90%tile seismic motion



Sensor correction **OFF**

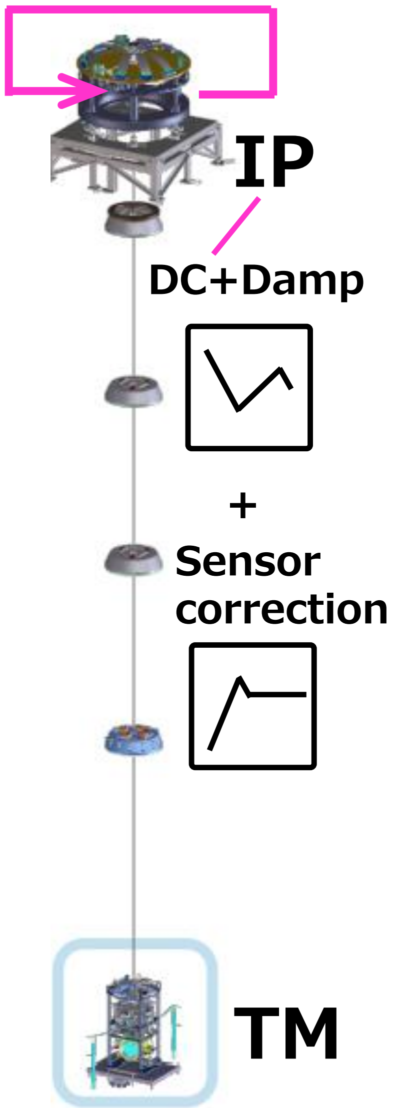


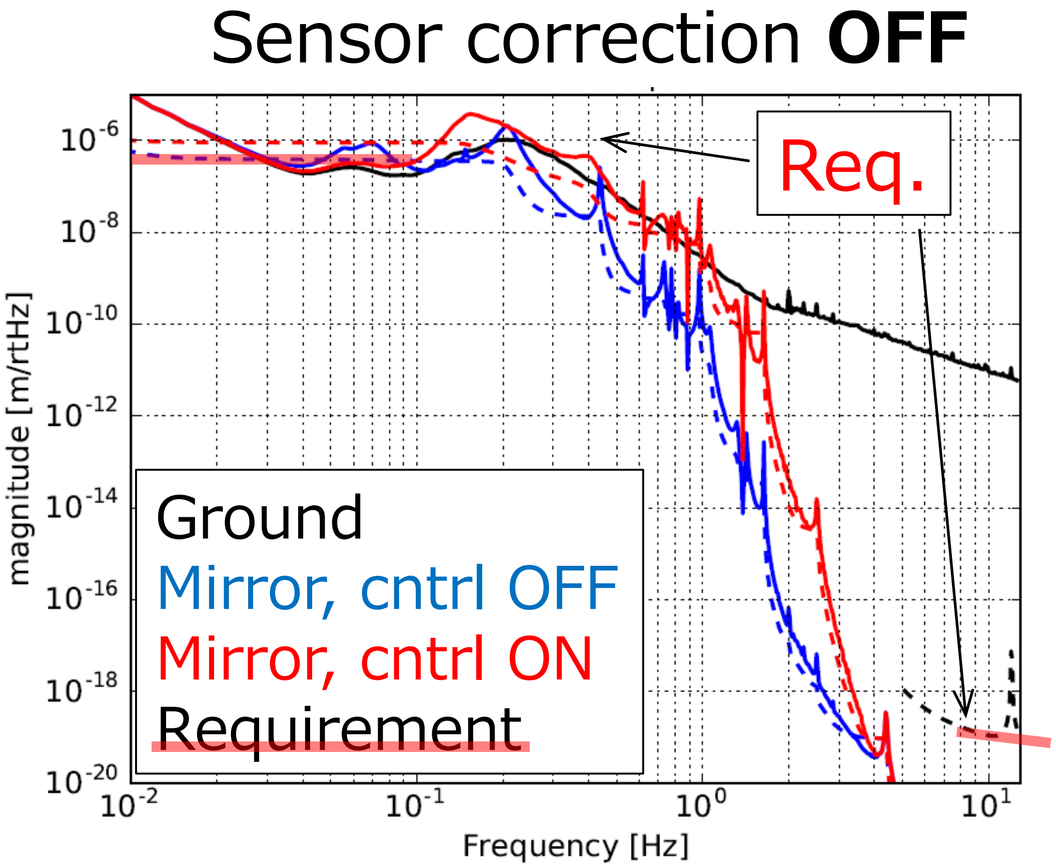
Sensor correction **ON**

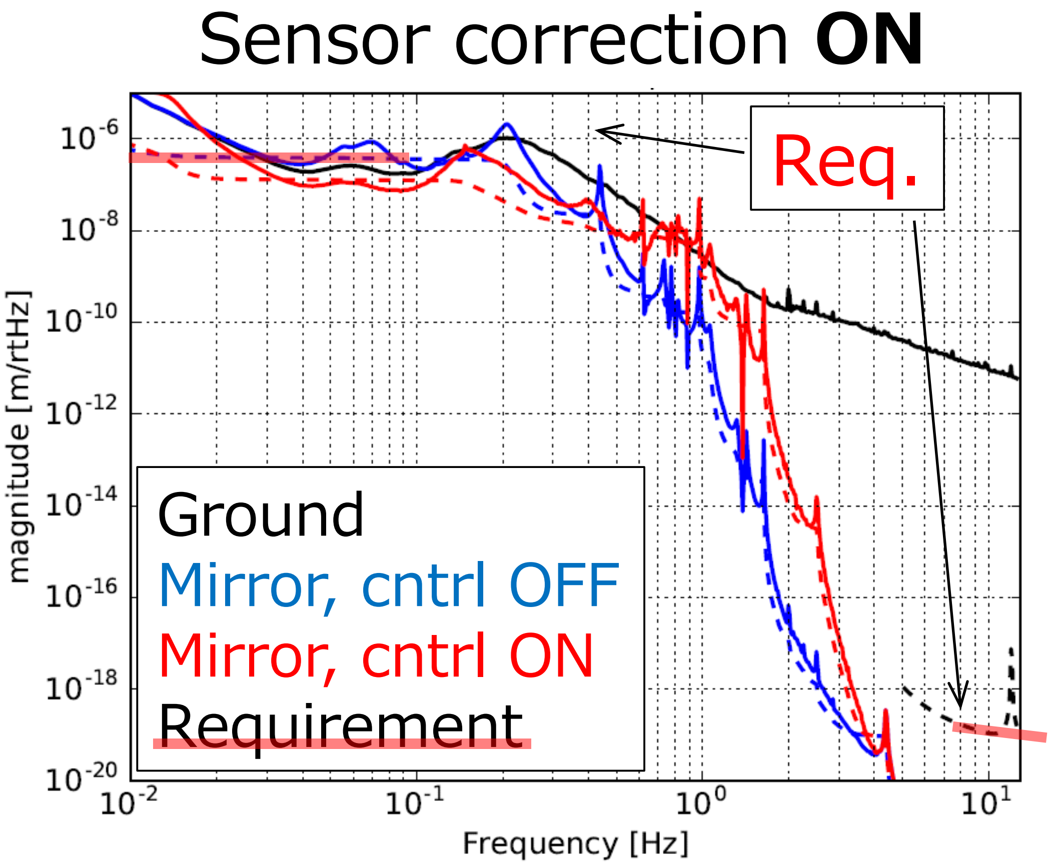


→ Sensor correction will satisfy requirement.

Simulation: mirror disp. w/ 90%tile seismic motion





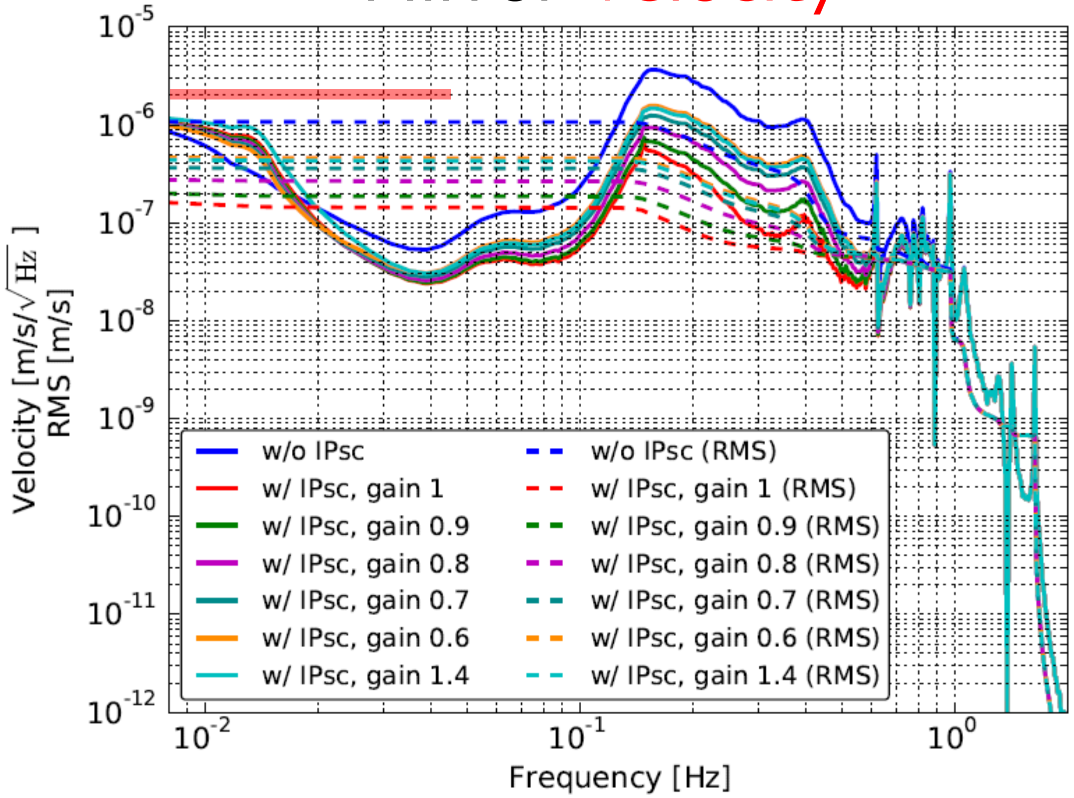


→ Sensor correction を用いて、要求値を満たせる。

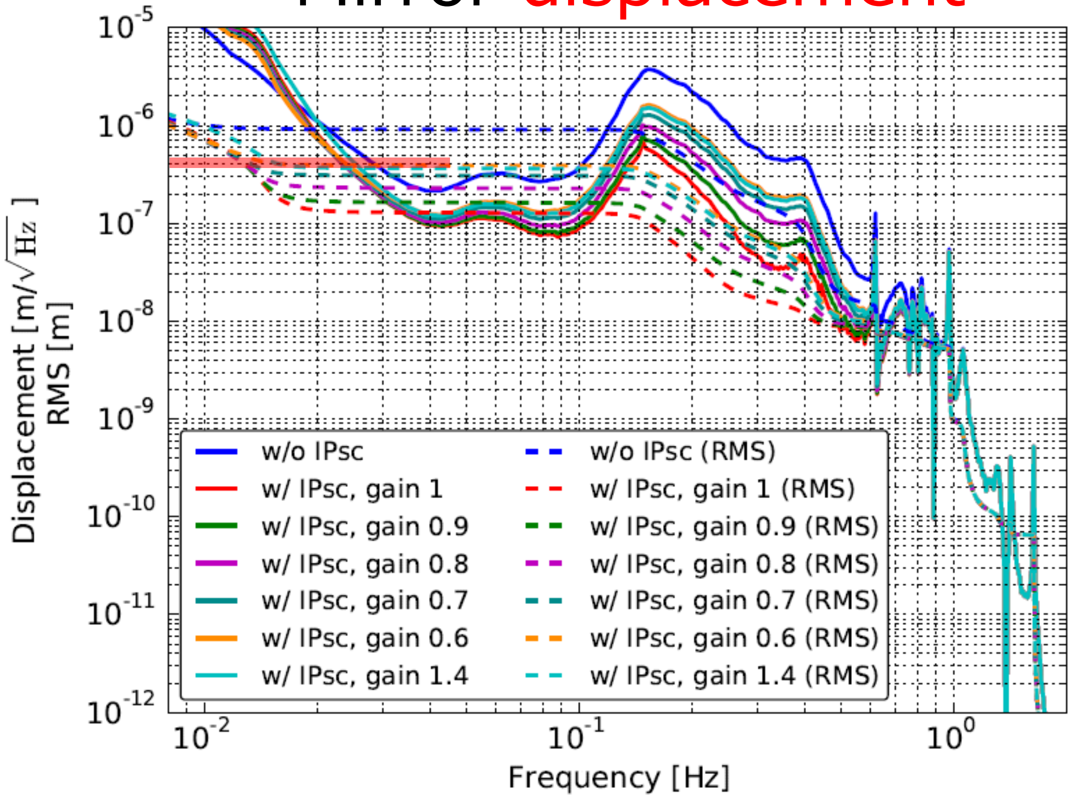
Simulation: mirror motion w/ 90%tile seismic motion

* Required precision of the inter-calibration:

Mirror velocity

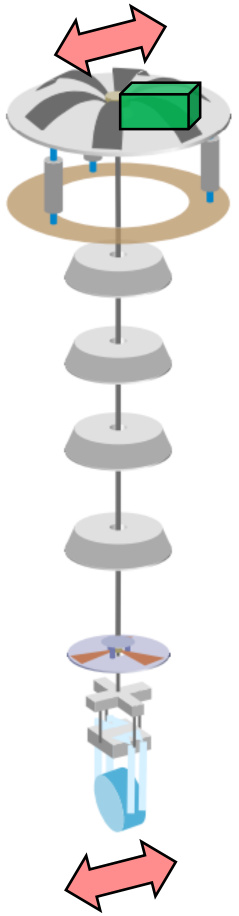


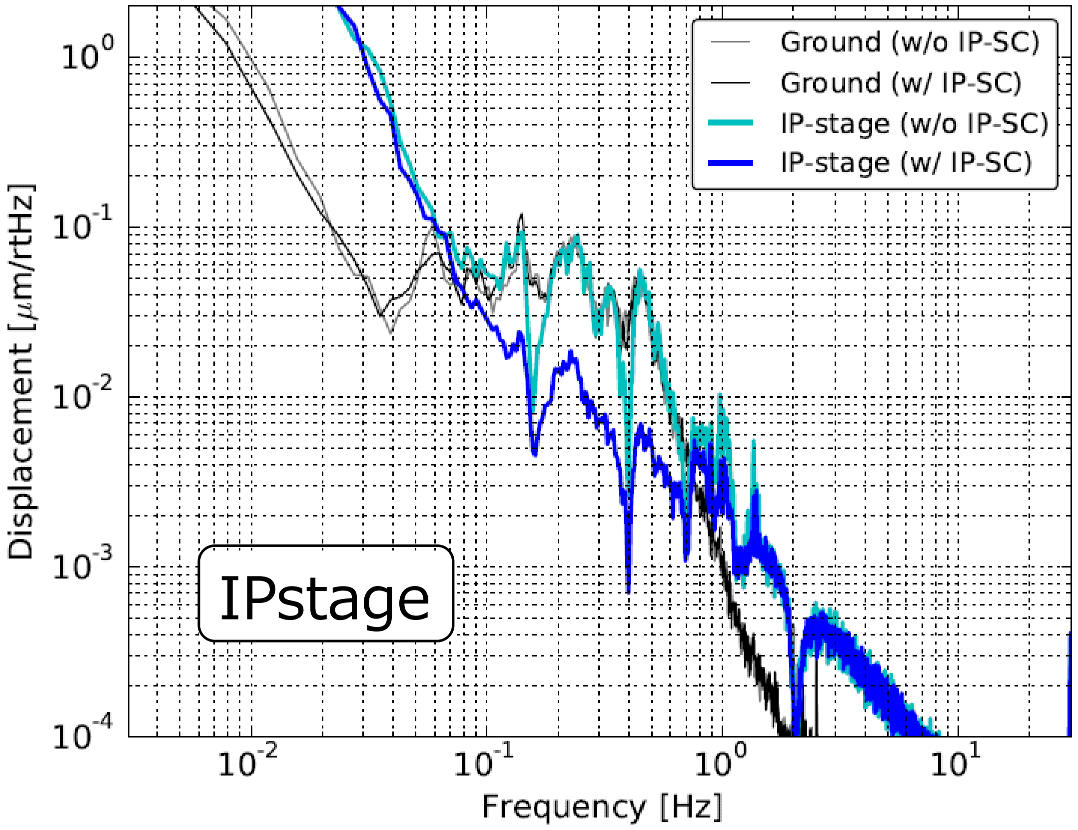
Mirror displacement

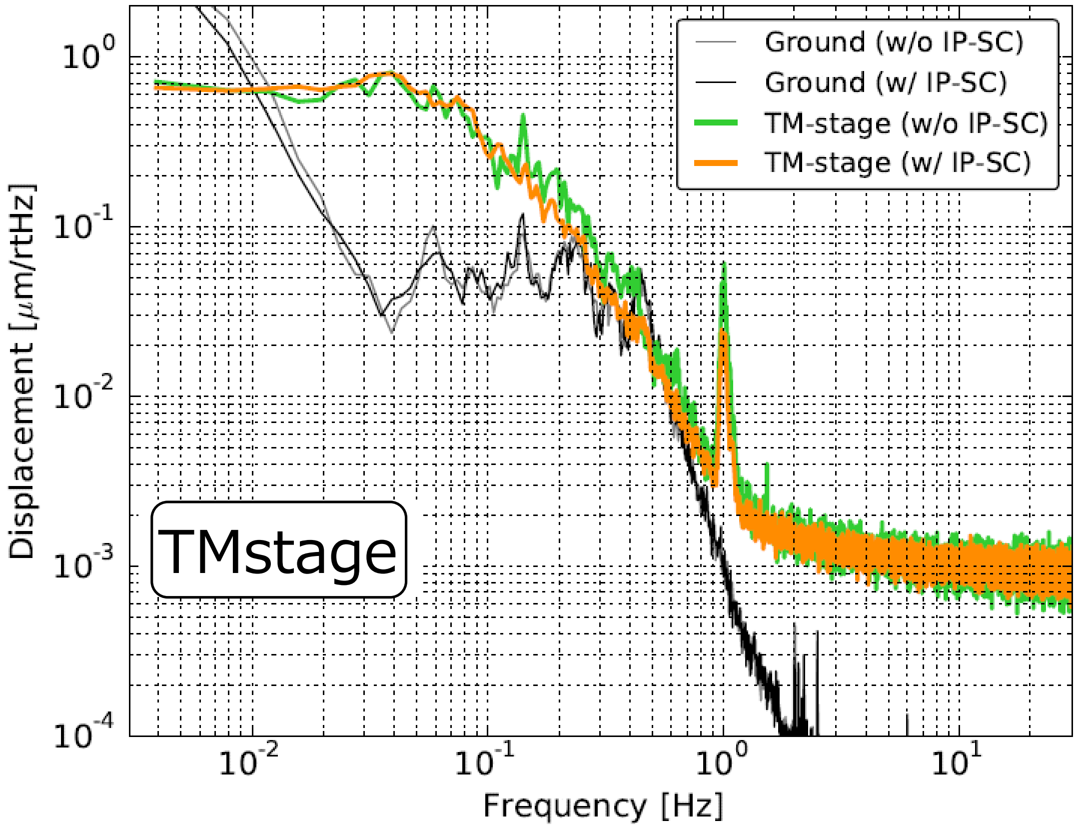


→ Necessary: seis/LVDT < 40% difference
→ Target: seis/LVDT < 10% difference

Improvement at IP- & TM-stage



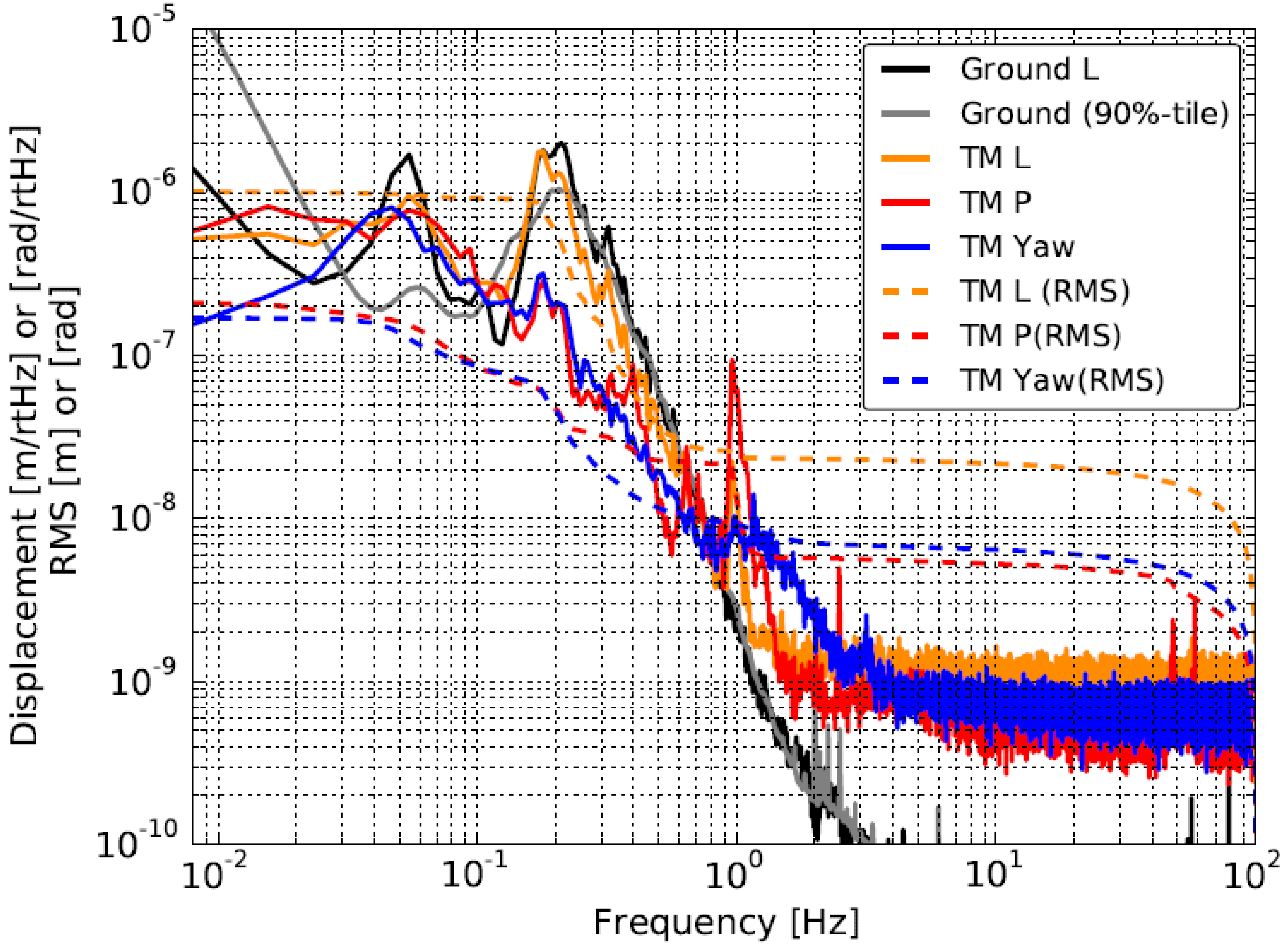




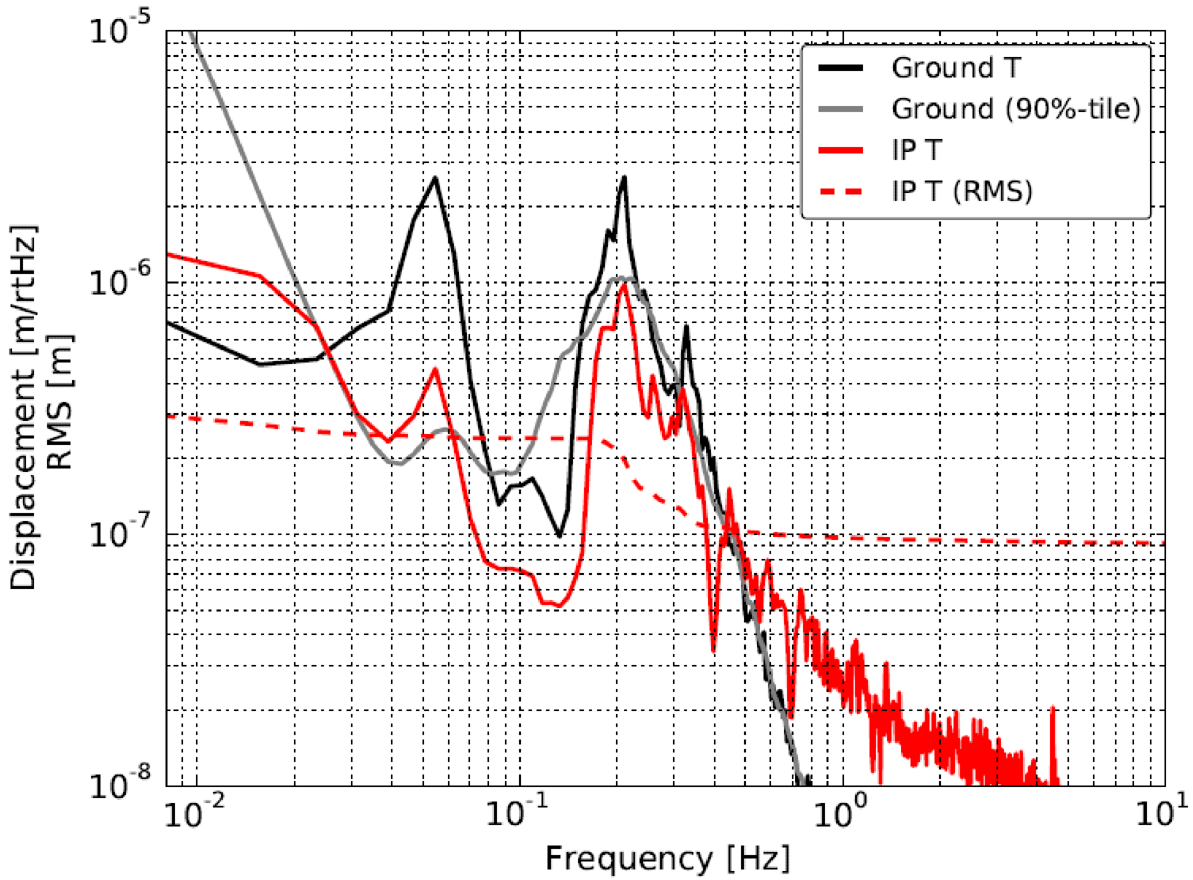
→ SC worked at 0.15 ~ 0.7Hz.

→ covered by TM oplev noise.

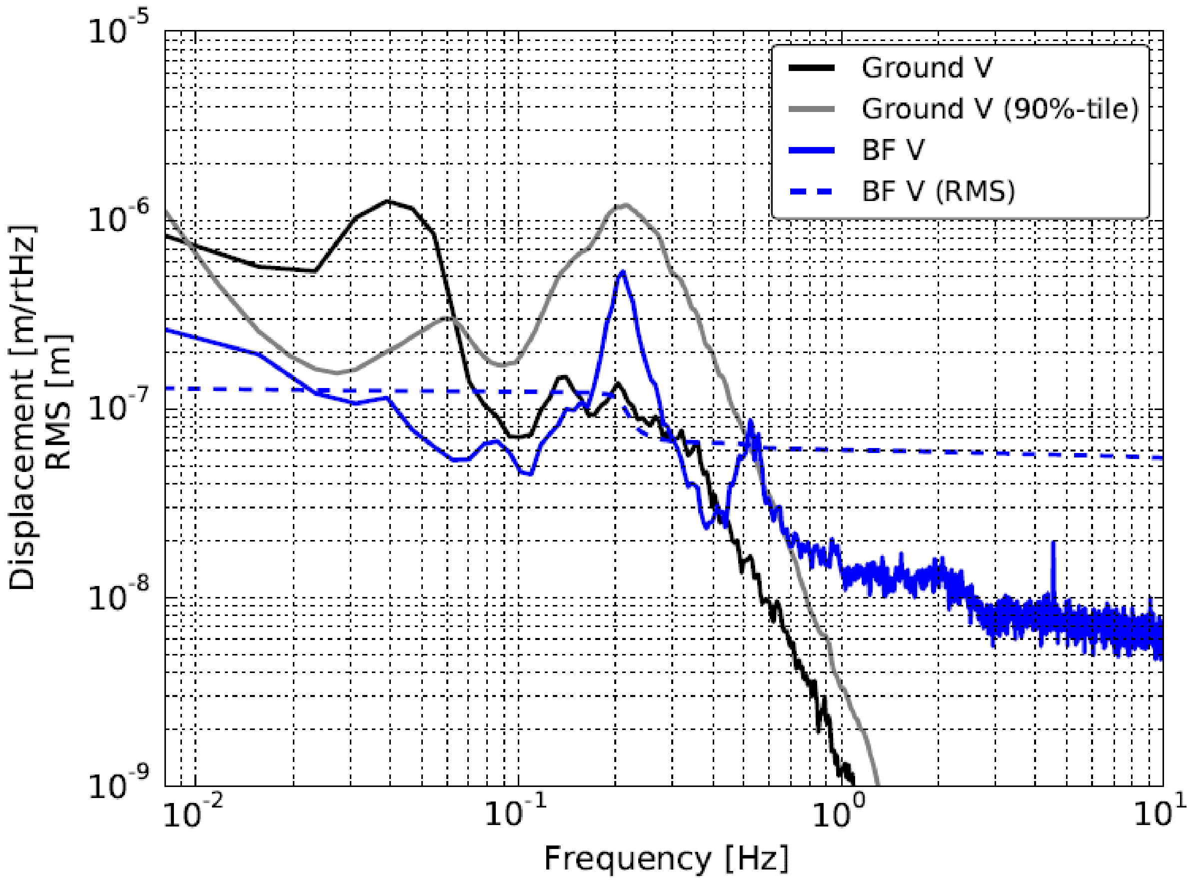
Mirror angular motion (RMS) in Pitch & Yaw



Estimated mirror motion (RMS) in Transverse & Vertical

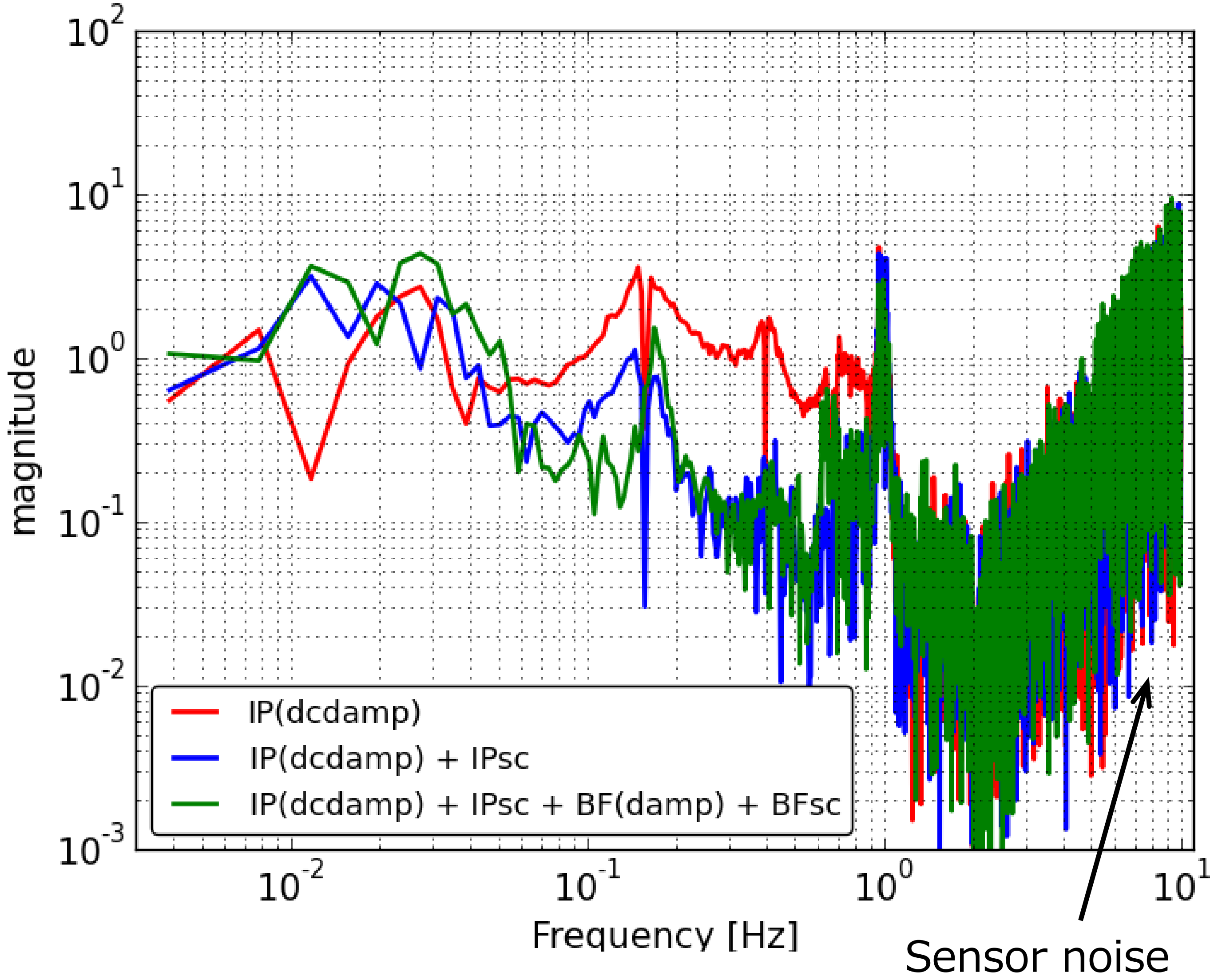


(Measured by geophone)



(Measured by BF-LVDT)

By combining (TML/IPL)*(IPL/GNDL)



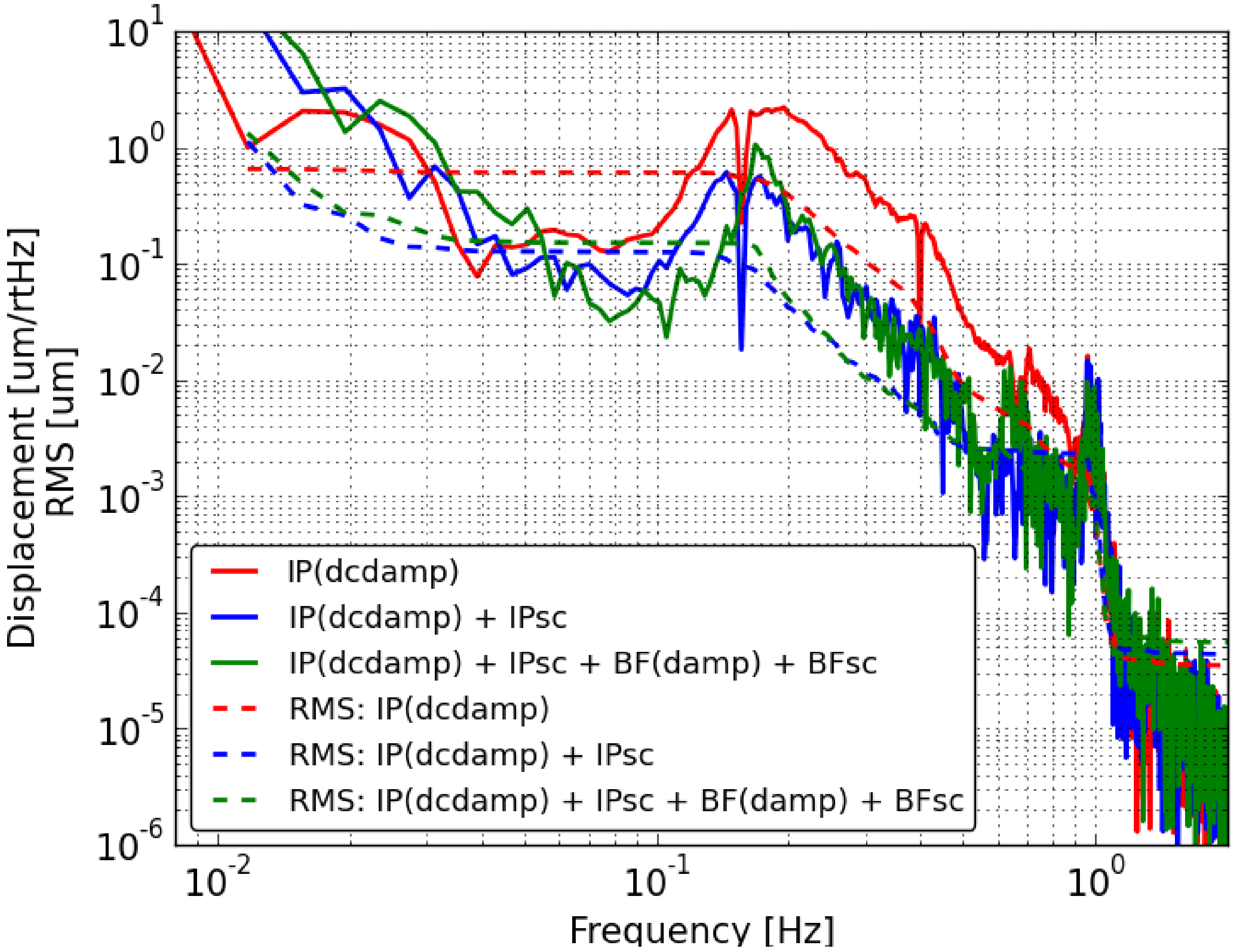
Displacement TF:
From GND to TML

(measured at ETMX)

Is notch real?
→ Not sure.
→ tilt coupling from Geophone
Or
→ Actual mechanical response

Whichever, the conclusion is same.

By combining (TML/IPL)*(IPL/GNDL)*(GNDL_model)

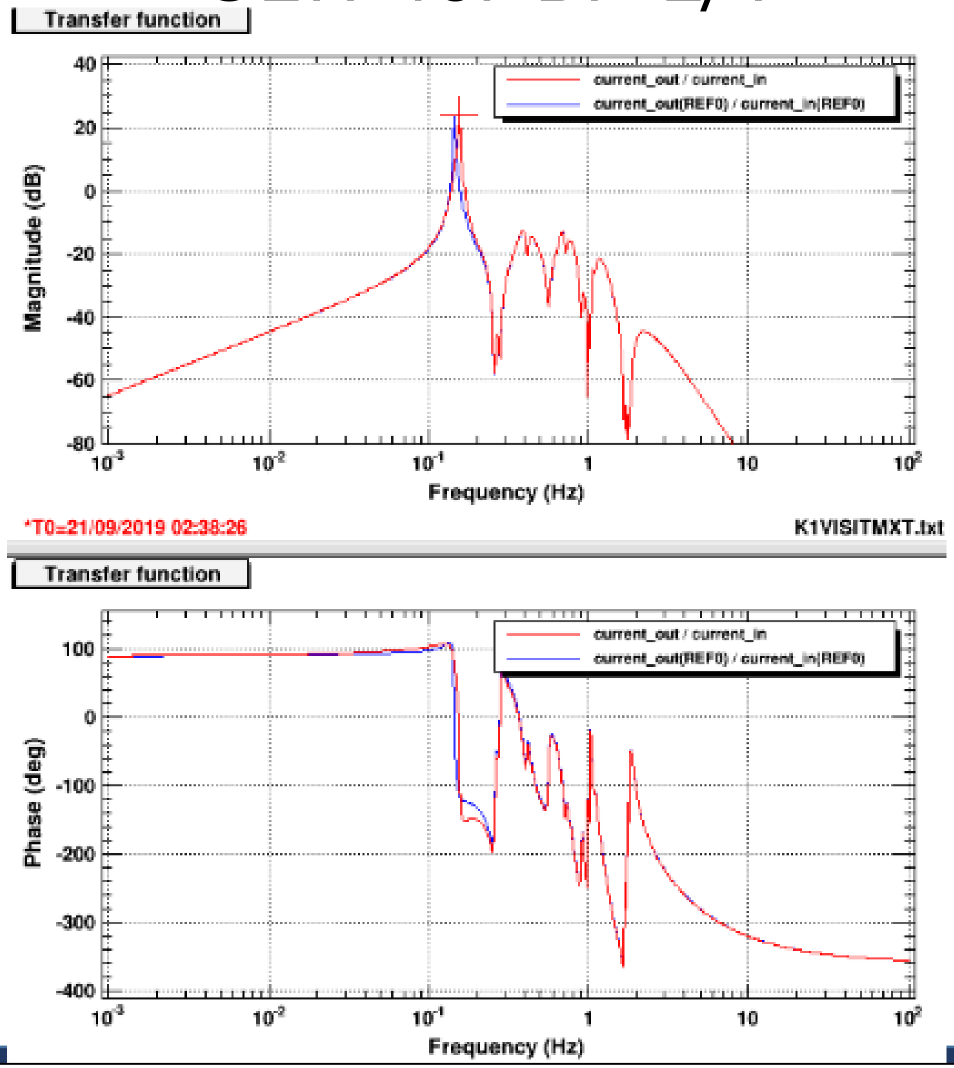


Disp. TF:

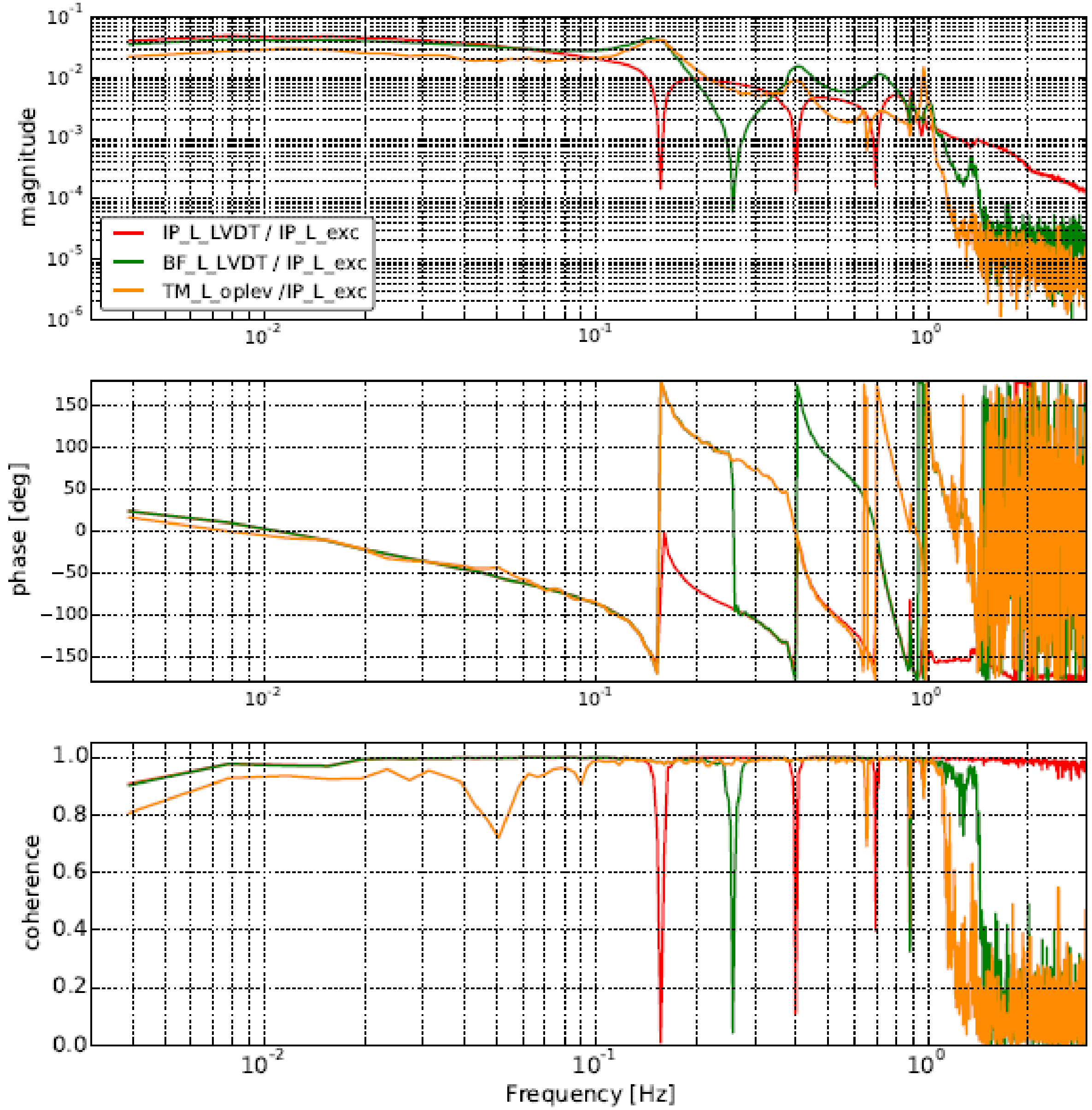
From GND to TML

Control loop for BF-L/T

OLTF for BF-L/T



TFs when IP loops are closed.

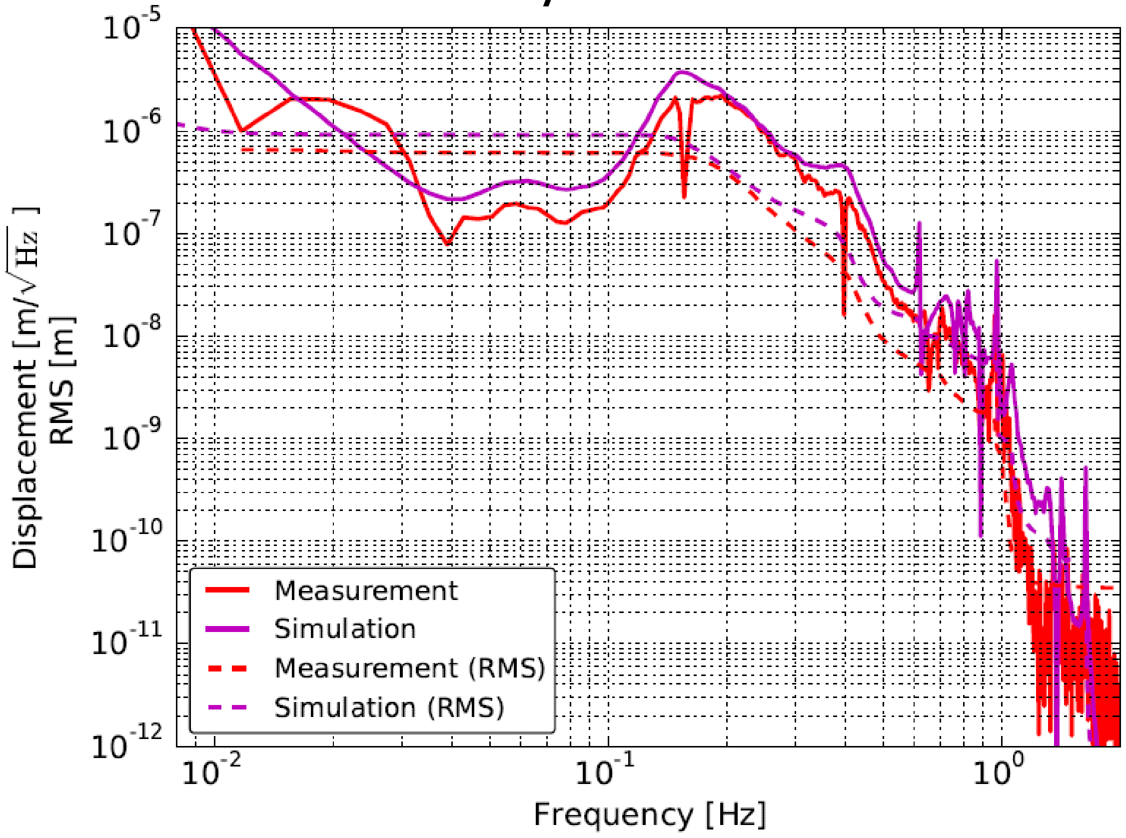


https://github.com/YoshinoriFujii/Weekly-task/issues/23

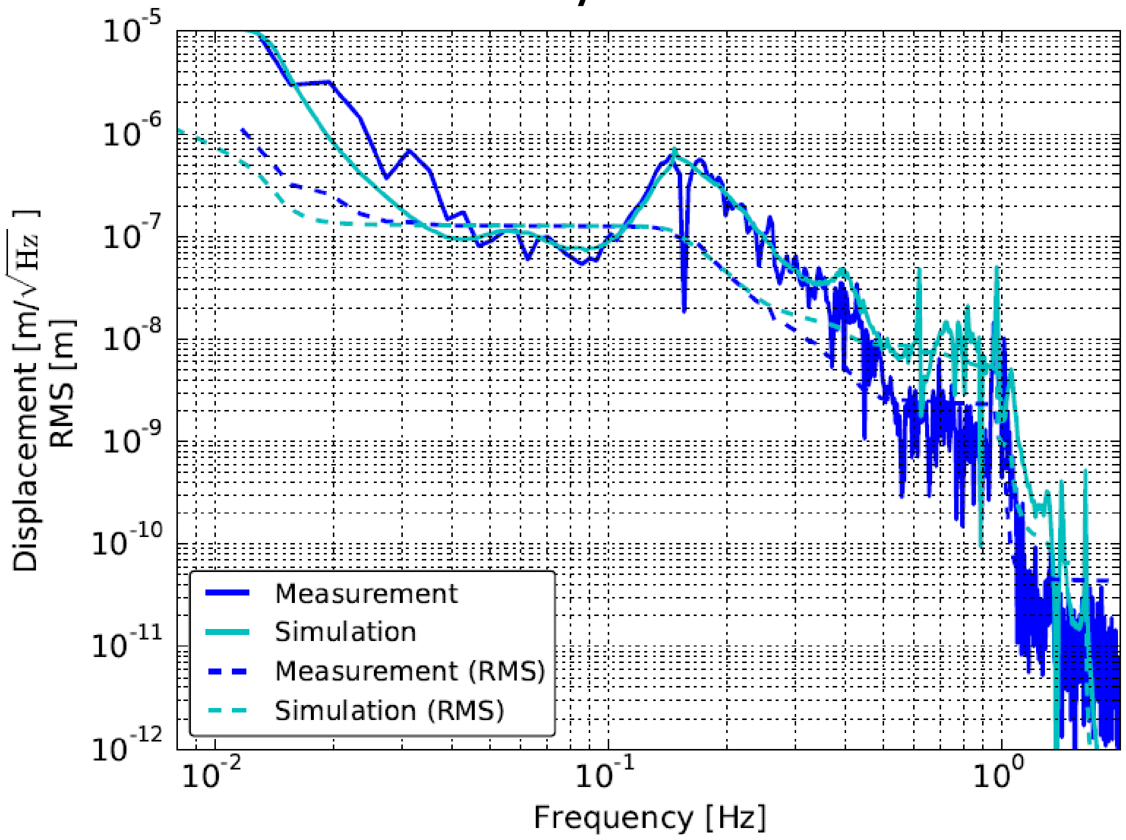
Comparison: simulation vs. measurement

* Mirror displacement w/ 90%tile seismic motion

w/o IPsc

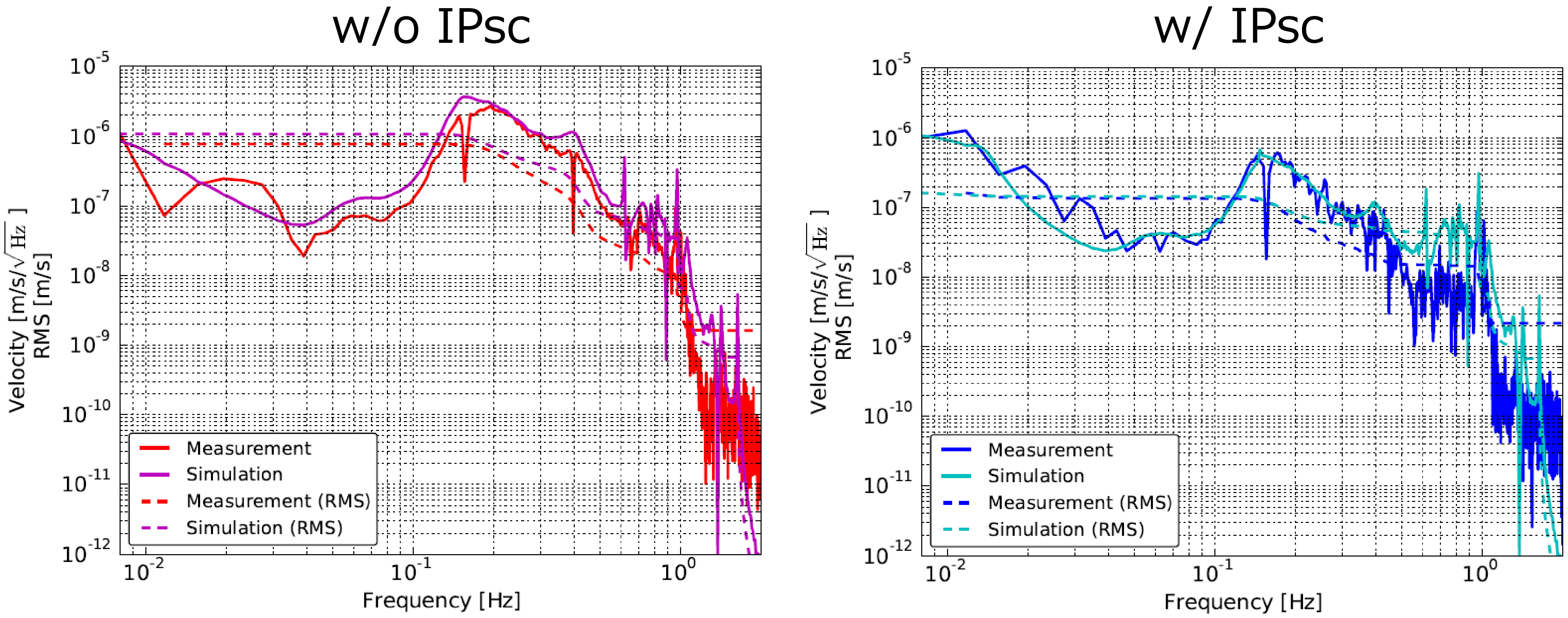


w/ IPsc



Comparison: simulation vs. measurement

* Mirror velocity w/ 90%tile seismic motion



3. Mirror residual suppression

* Options for further stabilization:

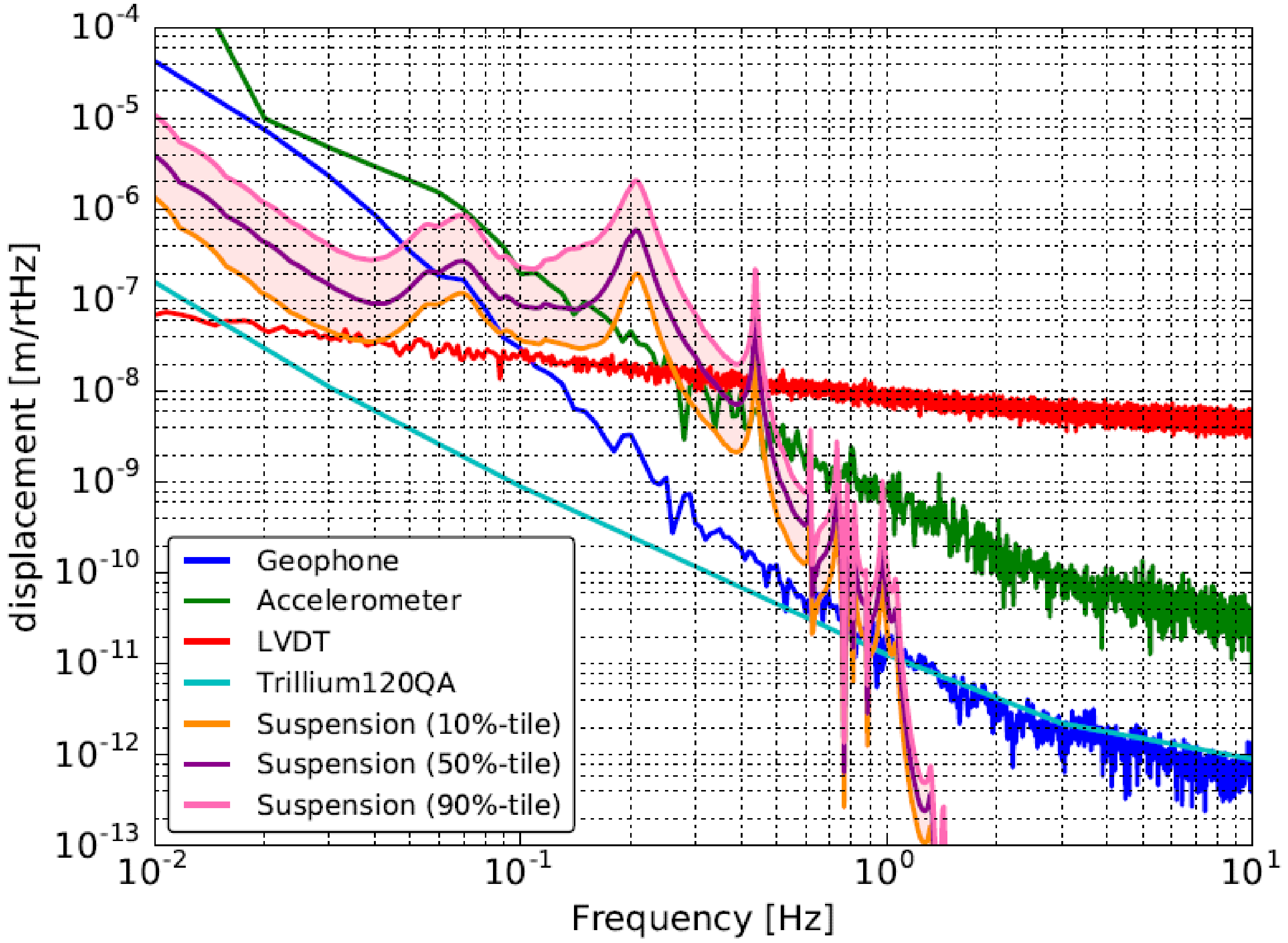
  * implement inertial damping system with sensitive inertial sensors.
    * For this, subtract tilt-signal from the inertial sensors with tilt-meter might be necessary.

  * locally subtract tilt-signal from seismometer with tilt-meter.

  * actuate the ETMs so that the their drifts follow that of ITMs with interferometer/cavity signal or strain-meter signal.

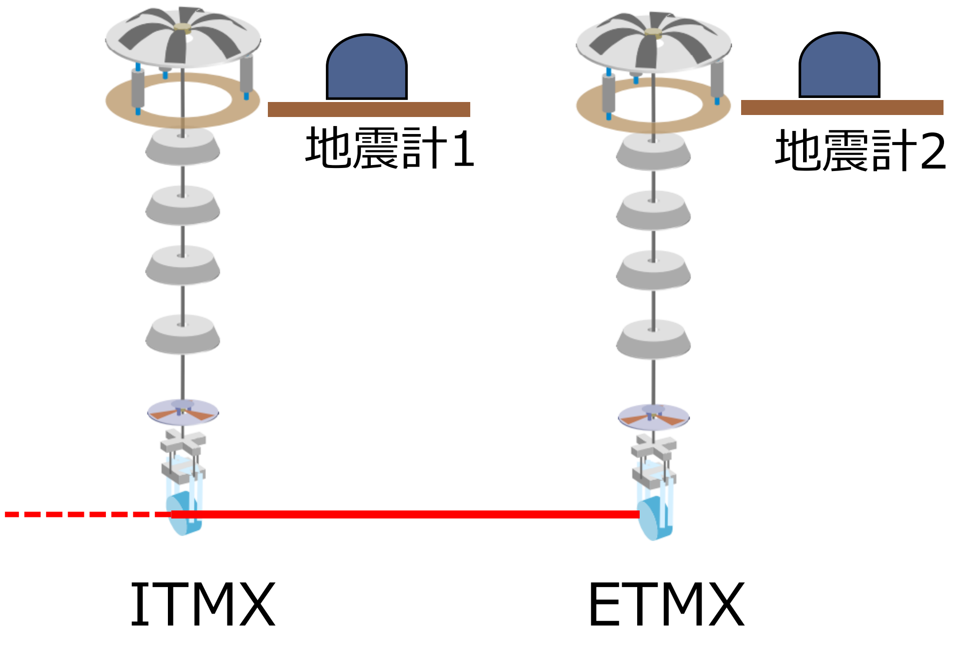
Sensor self-noise vs. mechanical response

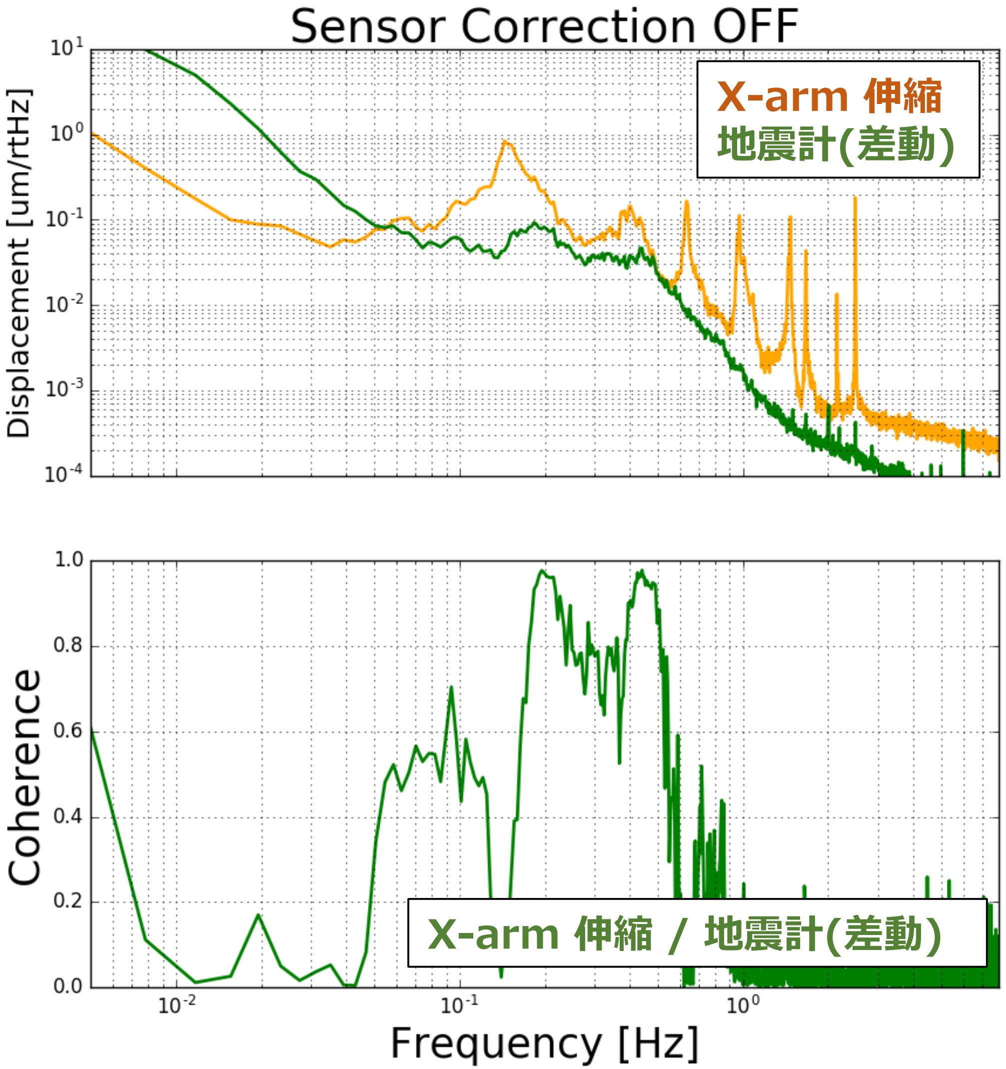
* w/ 10%tile, 50%tile and 90%tile seismic motion:



テスト実装: 2つのサスペンションのIP-stageに実装、Xarm で見ると

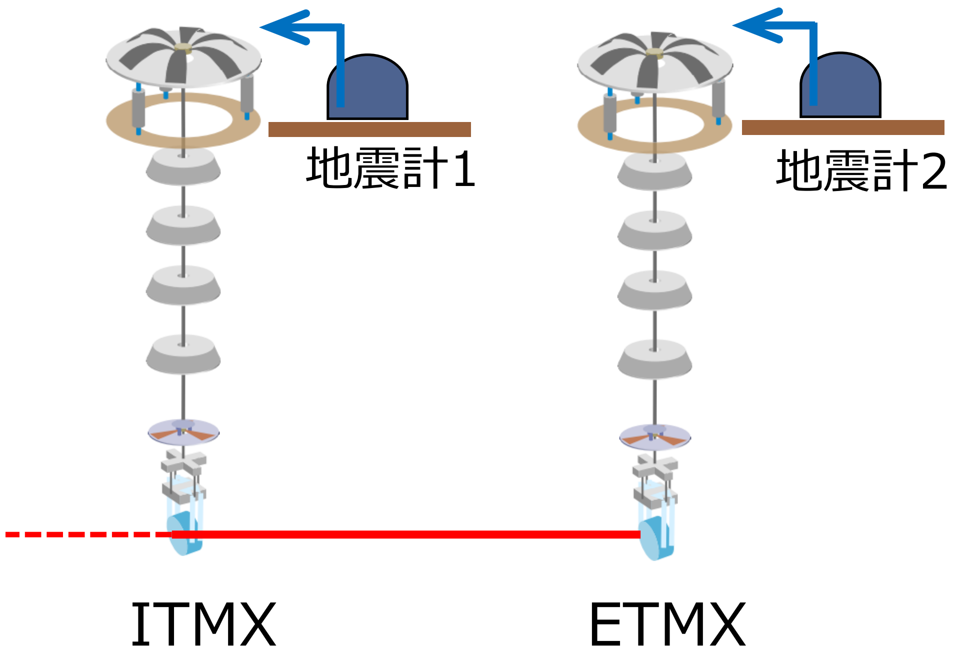
→ ETMX と ITMX に実装
  → 0.15 ~ 0.7 Hzにて同様な改善あり
→ X-arm (FP cavity) の共振器長の確認

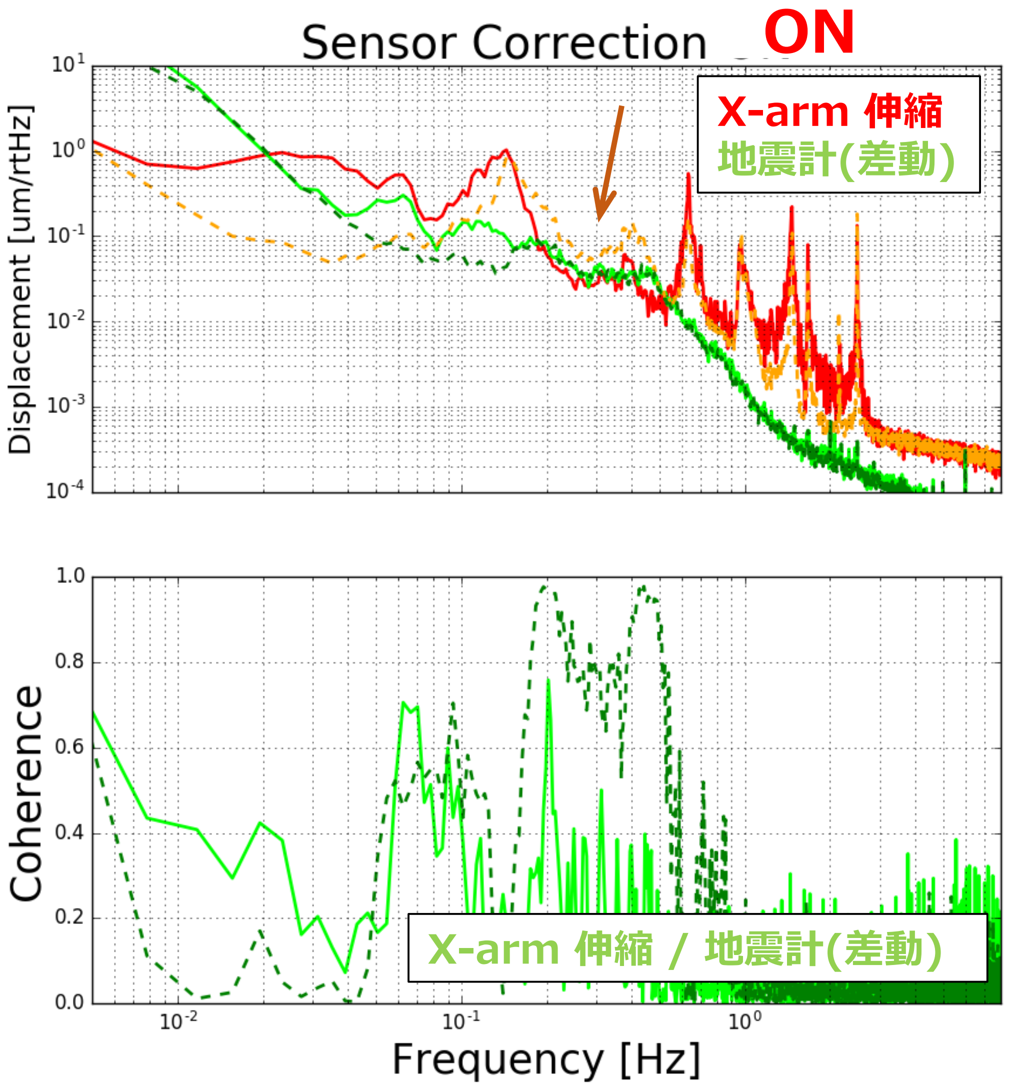




テスト実装: 2つのサスペンションのIP-stageに実装、Xarm で見ると

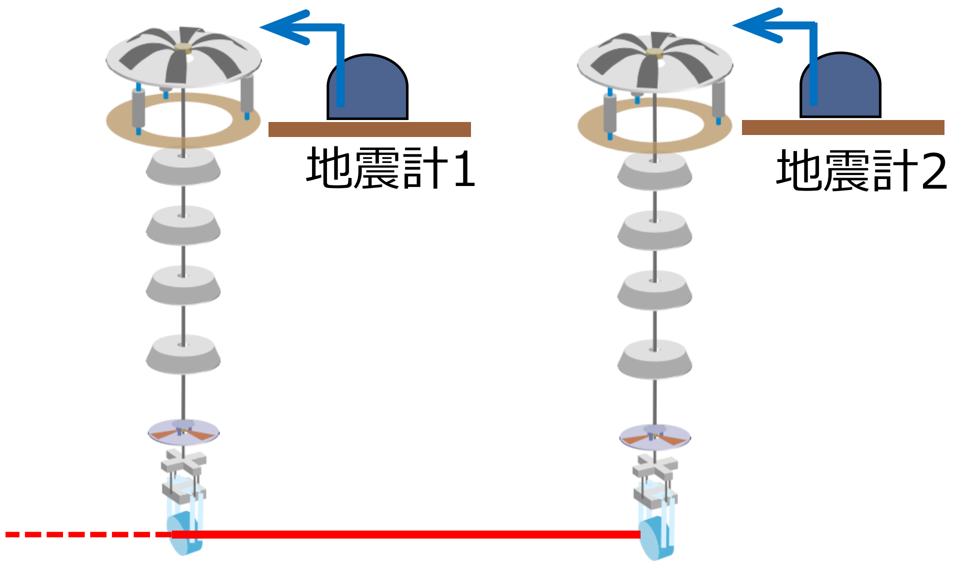
→ X-arm (FP cavity) の共振器長では

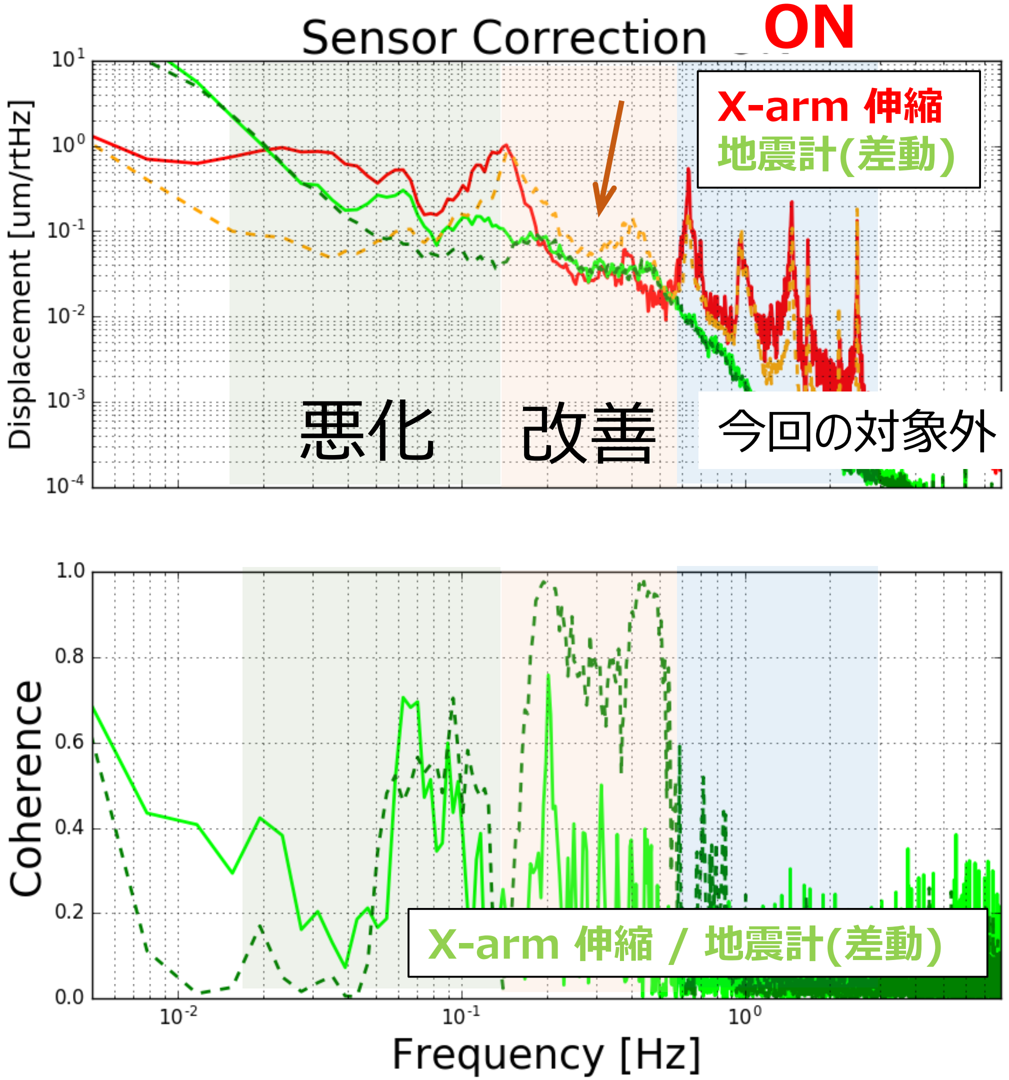




テスト実装: 2つのサスペンションのIP-stageに実装、Xarm で見ると

→ X-arm (FP cavity) の共振器長では

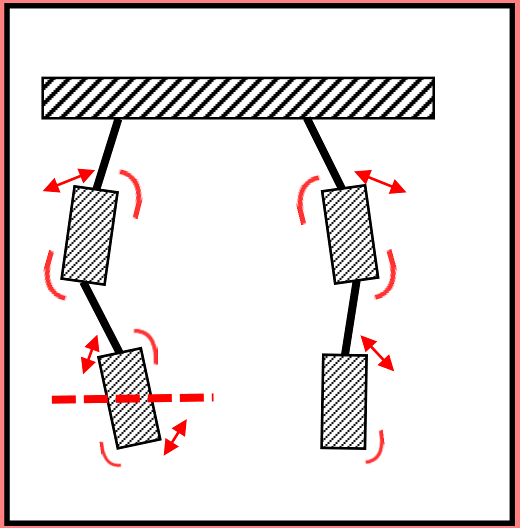




-- SC worked at 0.15 ~ 0.6Hz.
-- 低周波: 悪化
  → SC filterからの地震計の雑音の流入ほか
  → To be investigated.

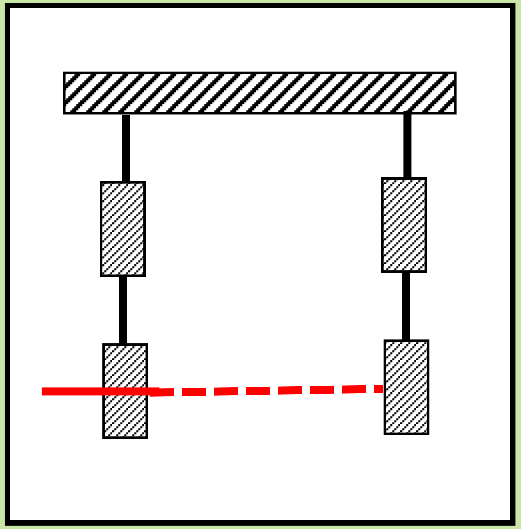
Designing active control system / Control phase

1. Calm-down phase



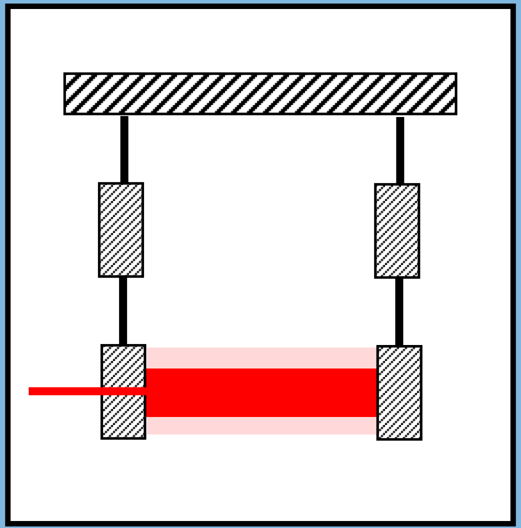
Suppress
large disturbance

2. Lock-acquisition phase



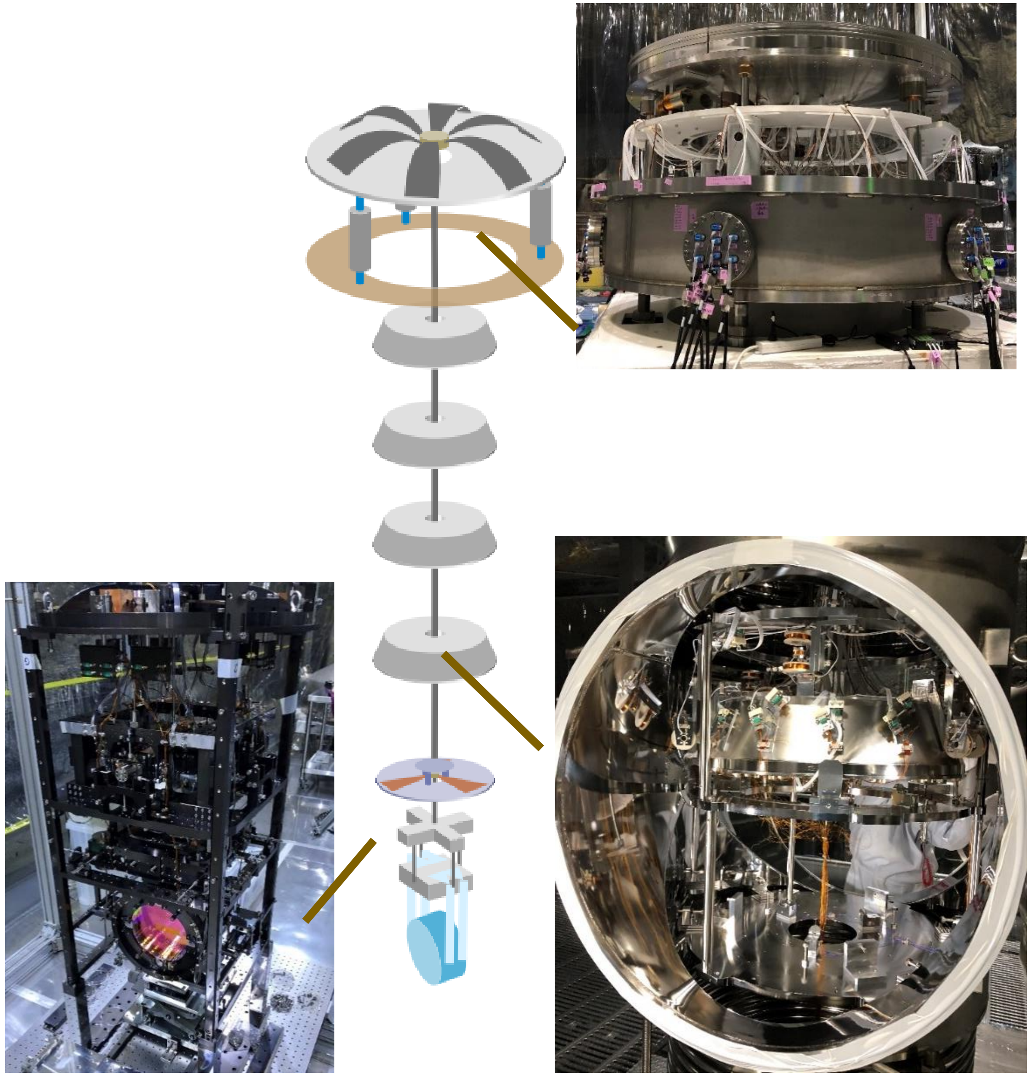
Reduce RMS velocity
RMS angle
(Root-Mean-Square)

3. Observation phase

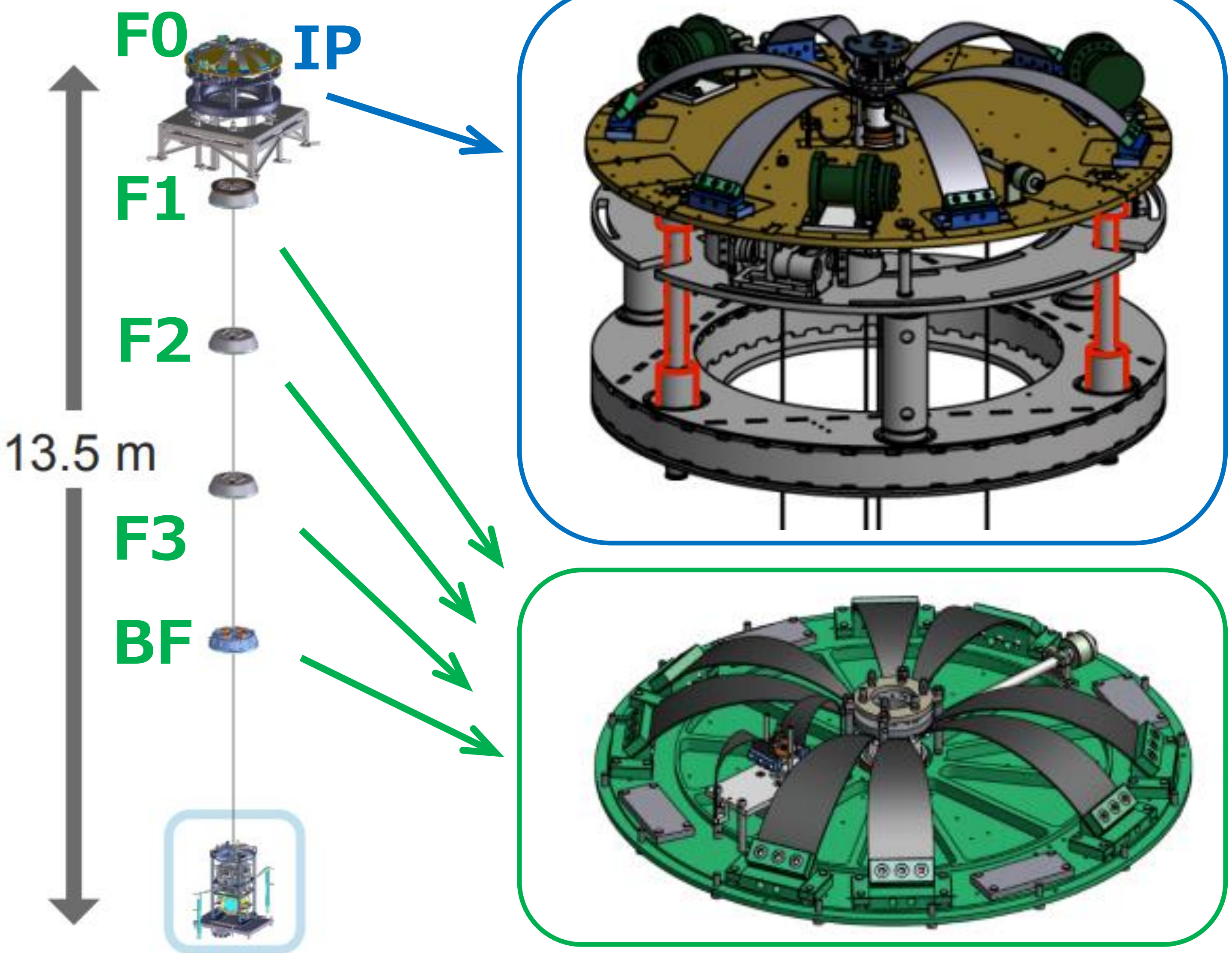


Keep position
with low noise
control

Type-A suspension



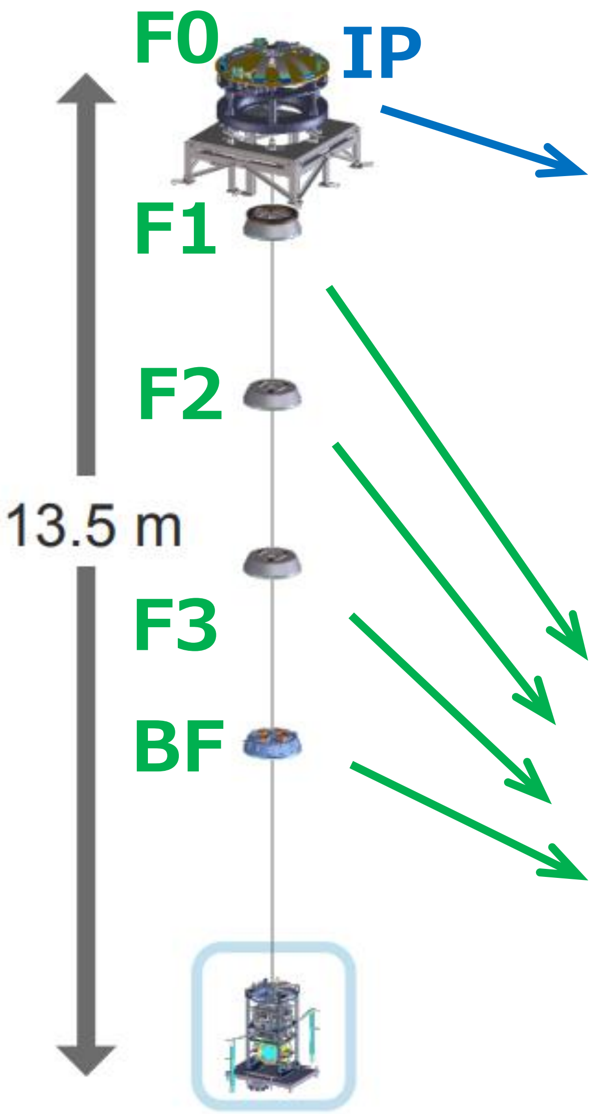
メイン鏡用の防振装置

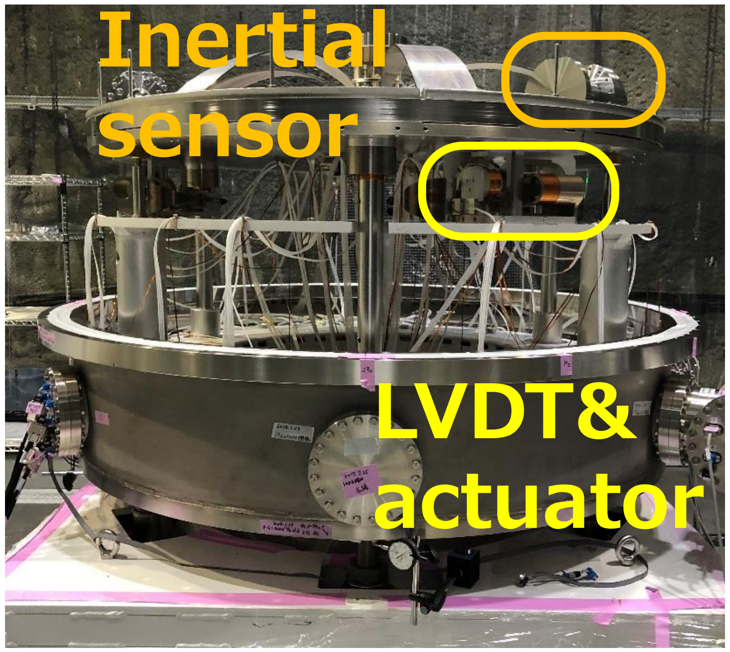


INVERTED PENDULUM
(~ 70 mHz)

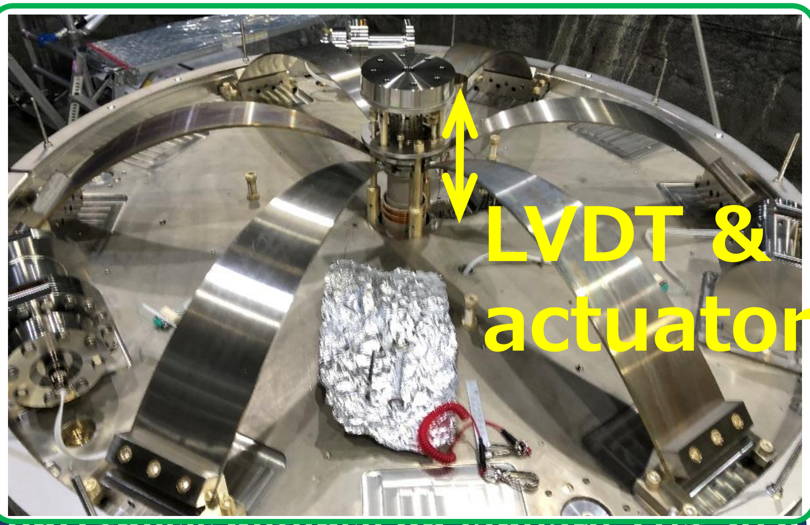
GEOMETRIC-ANTI SPRING
(~ 0.4 Hz)

メイン鏡用の防振装置





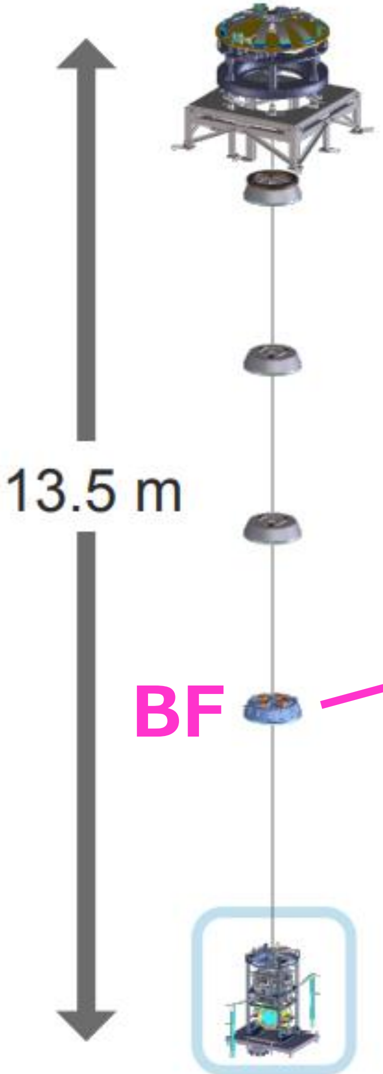
INVERTED PENDULUM
with 3 horizontal
-- LVDT & actuator units
-- inertial sensors



GEOMETRIC-ANTI SPRING
with 1 vertical
LVDT & actuator unit

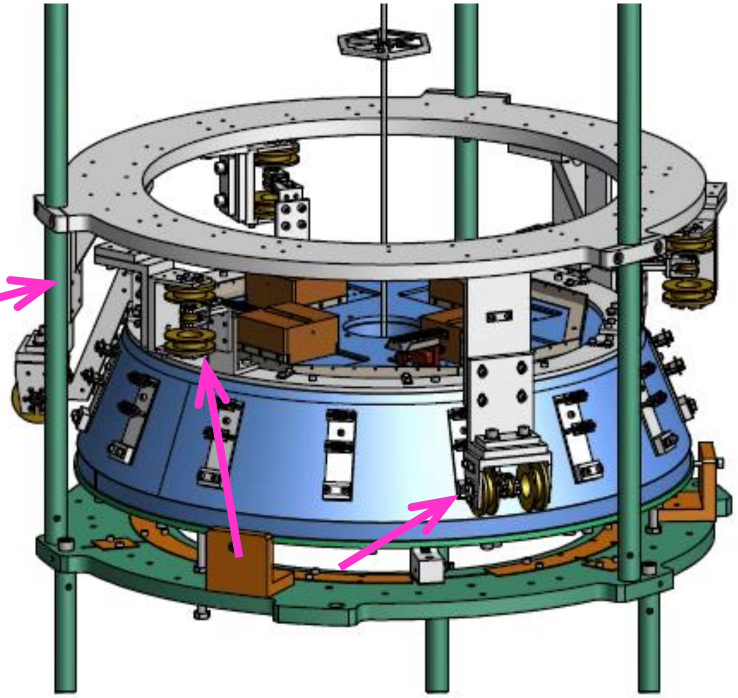
メイン鏡用の防振装置

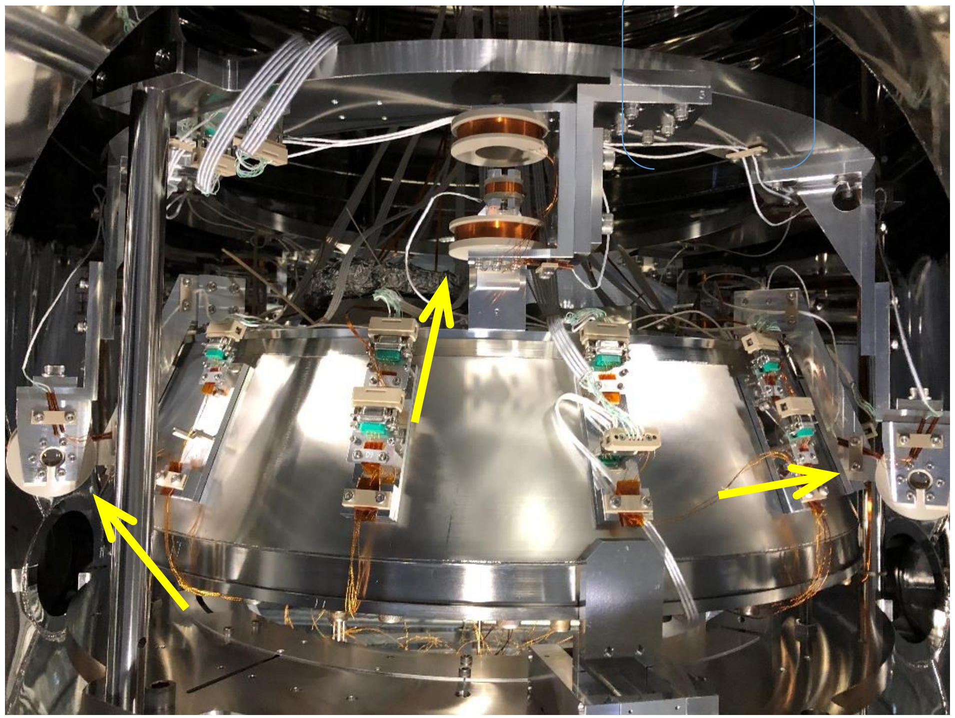
(イタリアのグループの協力のもと開発)



BOTTOM-FILTER DAMPER

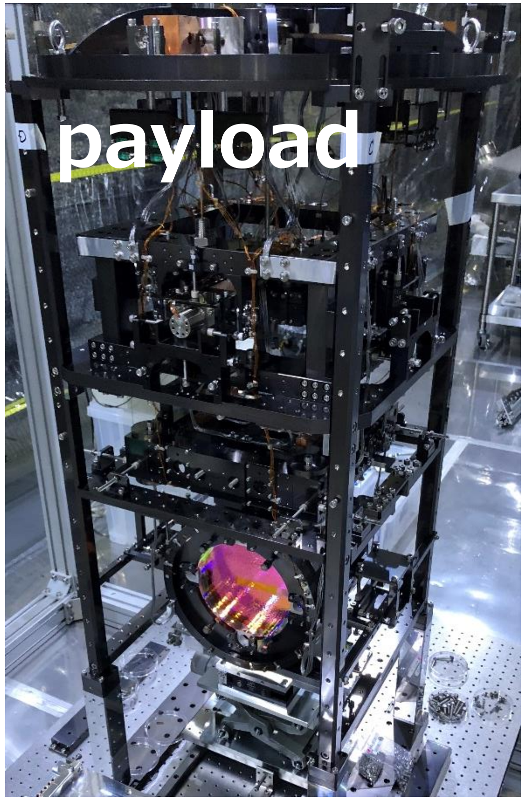
with 3 horizontal & 3 vertical LVDT & actuator units



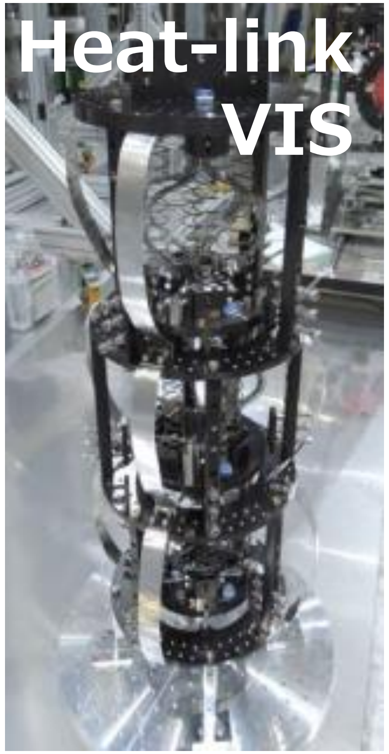


And, the cryogenic part

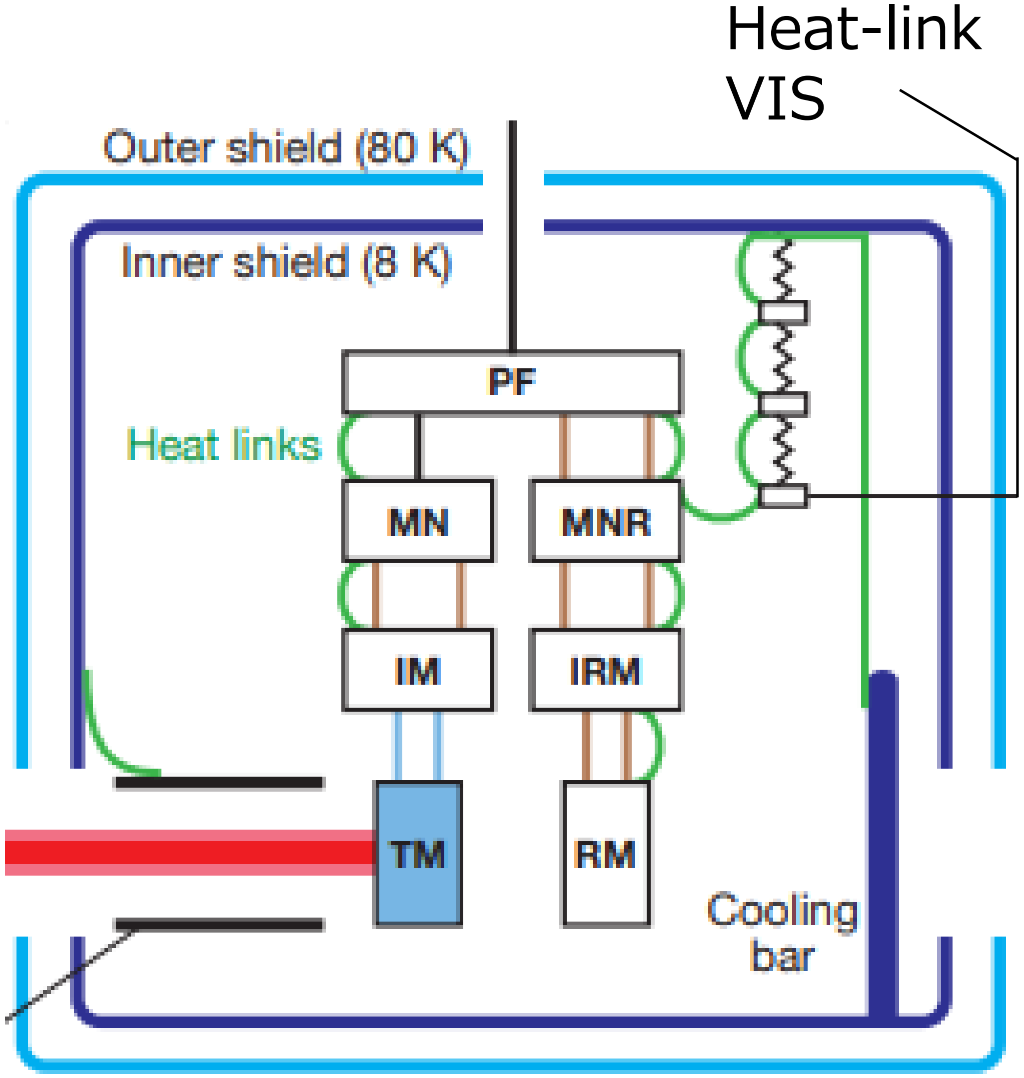
Inside cryostat



+



(+ Wide-angle baffle)



JGW-P1809347

Requirements, Type-A suspensions by YF

Table 5.2: Requirements on the Type-A suspension control. The column labeled as ref. describes the section which explains the reason of the requirements.

Items	Requirements	ref.
The calm-down phase		
$1/e$ decay time	$<$ 1 min.	§ 5.1.2
RMS displacement (transverse, vertical)	$<$ 0.1 mm	§ 5.1.6
The lock acquisition phase		
RMS velocity (longitudinal)	$< 2.0\ \mu$m/sec.	§ 5.1.3
RMS angle (pitch, yaw)	$<$ 880 nrad	§ 5.1.4
RMS displacement (longitudinal)	$< 0.39\ \mu$m	§ 5.1.5
RMS displacement (transverse, vertical)	$<$ 0.1 mm	§ 5.1.6
The observation phase		
Control noise at 10 Hz (longitudinal)	$< 8.0 \times 10^{-20}\ \mathrm{m}/\sqrt{\mathrm{Hz}}$	§ 4.2
RMS displacement (longitudinal)	$< 0.39\ \mu$m	§ 5.1.5
RMS displacement (transverse, vertical)	$<$ 0.1 mm	§ 5.1.6
RMS angle (pitch, yaw)	$<$ 200 nrad	§ 5.1.4
DC angle drift (pitch, yaw)	$<$ 400 nrad	§ 5.1.4

Requirements, Type-A suspensions by KO

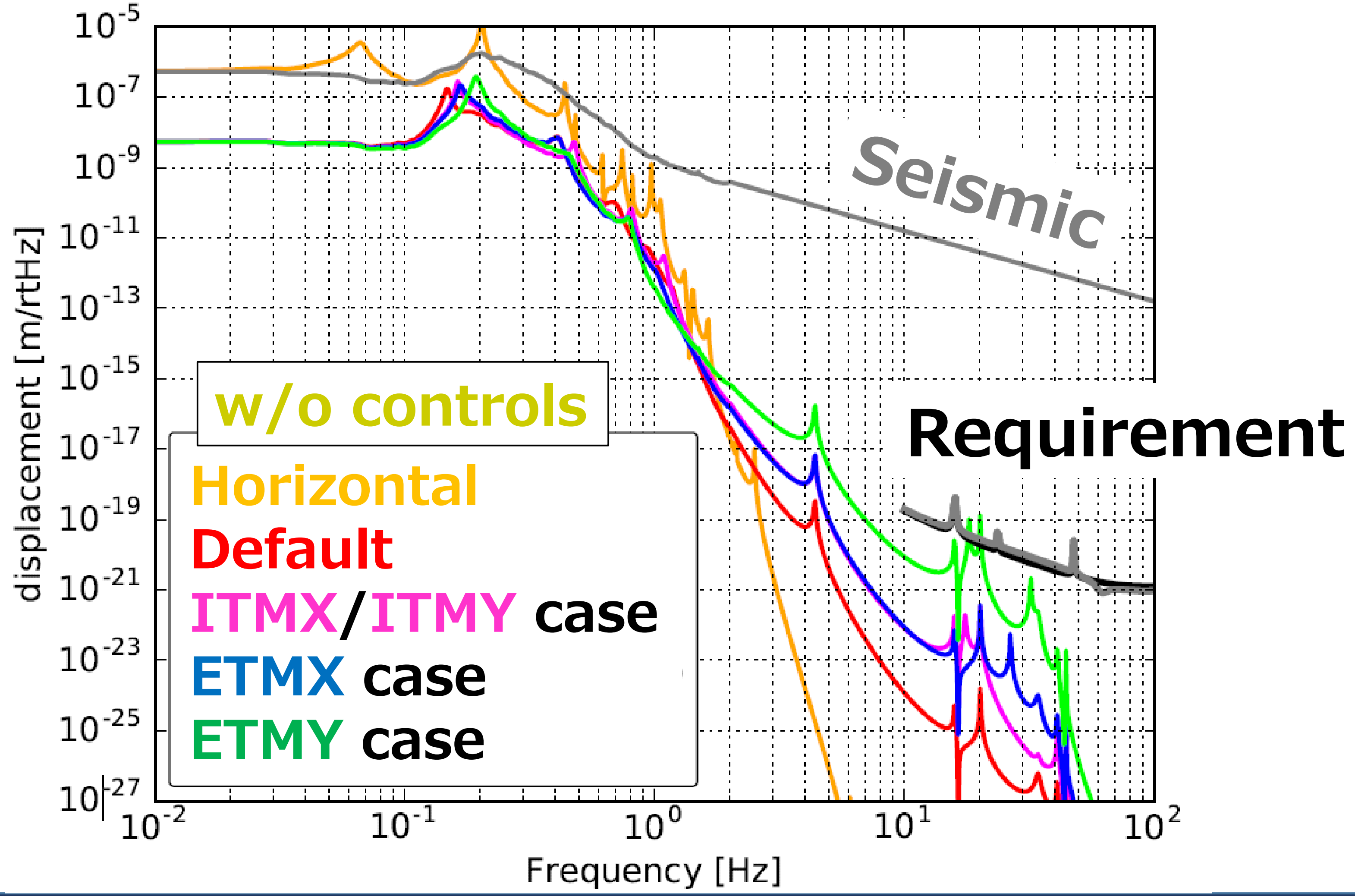
Calm-down phase		
Item	Requirement	For/Determined by
$1/e$ modal decay time	< 1 min	Quick recovery
RMS displacement (L)	$< 50\ \mu$m	Smooth transition to next phase
RMS displacement (T, V)	< 0.1 mm	Miscentering
RMS angle (P, Y)	$< 50\ \mu$m	Smooth transition to next phase
Lock acquisition phase		
Item	Requirement	For/Determined by
RMS velocity (L)	$< 240\ \mu$m/s	Auxiliary laser locking
RMS displacement (T, V)	< 0.1 mm	Miscentering
RMS angle (P, Y)	< 880 nrad	Optical gain degradation $< 5\%$
Observation phase		
Item	Requirement	For/Determined by
Displacement noise (L) @ 10 Hz	$< 8 \times 10^{-20}$ m/Hz$^{1/2}$	Sensitivity
Displacement noise (V) @ 10 Hz	$< 8 \times 10^{-18}$ m/Hz$^{1/2}$	Sensitivity (1% coupling to L)
RMS displacement (T, V)	< 0.1 mm	Miscentering
RMS angle (P, Y)	< 200 nrad	Beam spot fluctuation < 1 mm
DC drift (P, Y)	< 400 nrad/h	Sustainable lock for 1 day left

(P, Y) are set as $50\,\mu$m and $50\,\mu$rad, respectively [28]. The RMS displacement for the other translational DoFs (T, V) are required for another reason which is mentioned shortly later.

[ref] K. Okutomi PhD

Mechanical installation has done! HOWEVER ..

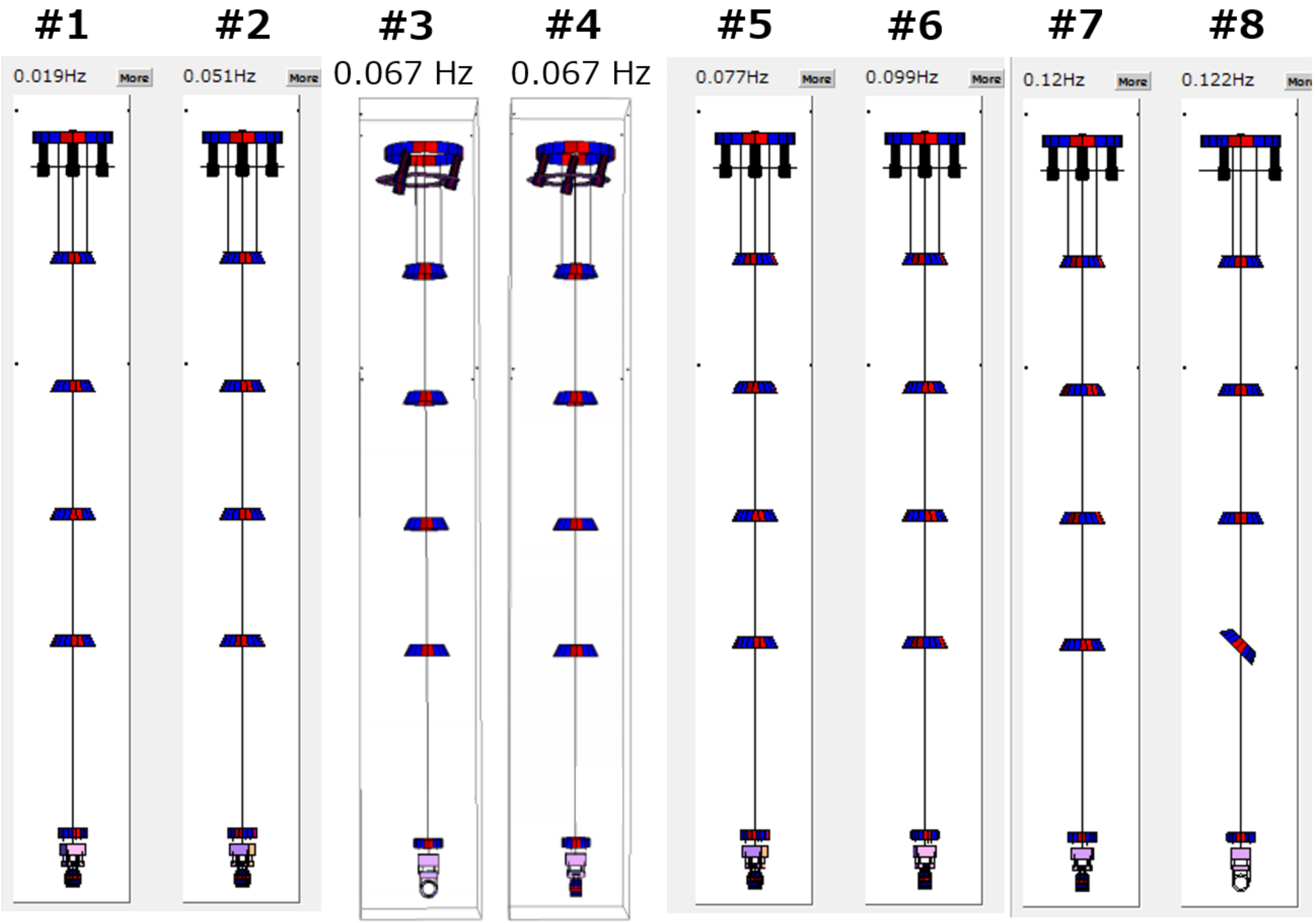
According to a simulation, assuming 1% coupling,



"acceptable for the O3-run"

(should be)

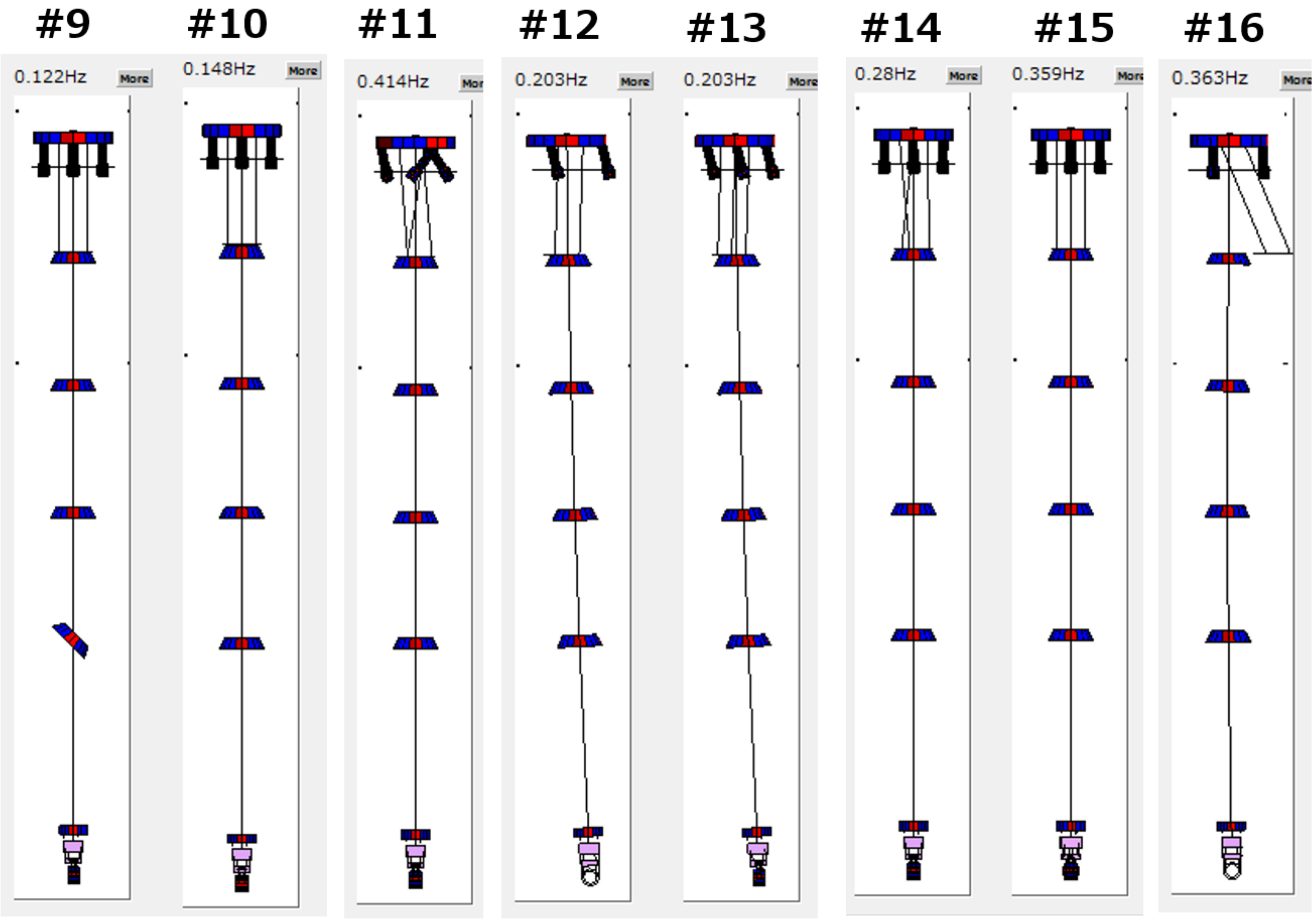
Note:
-- Modeled w/o Heat-links
-- params are not tuned.

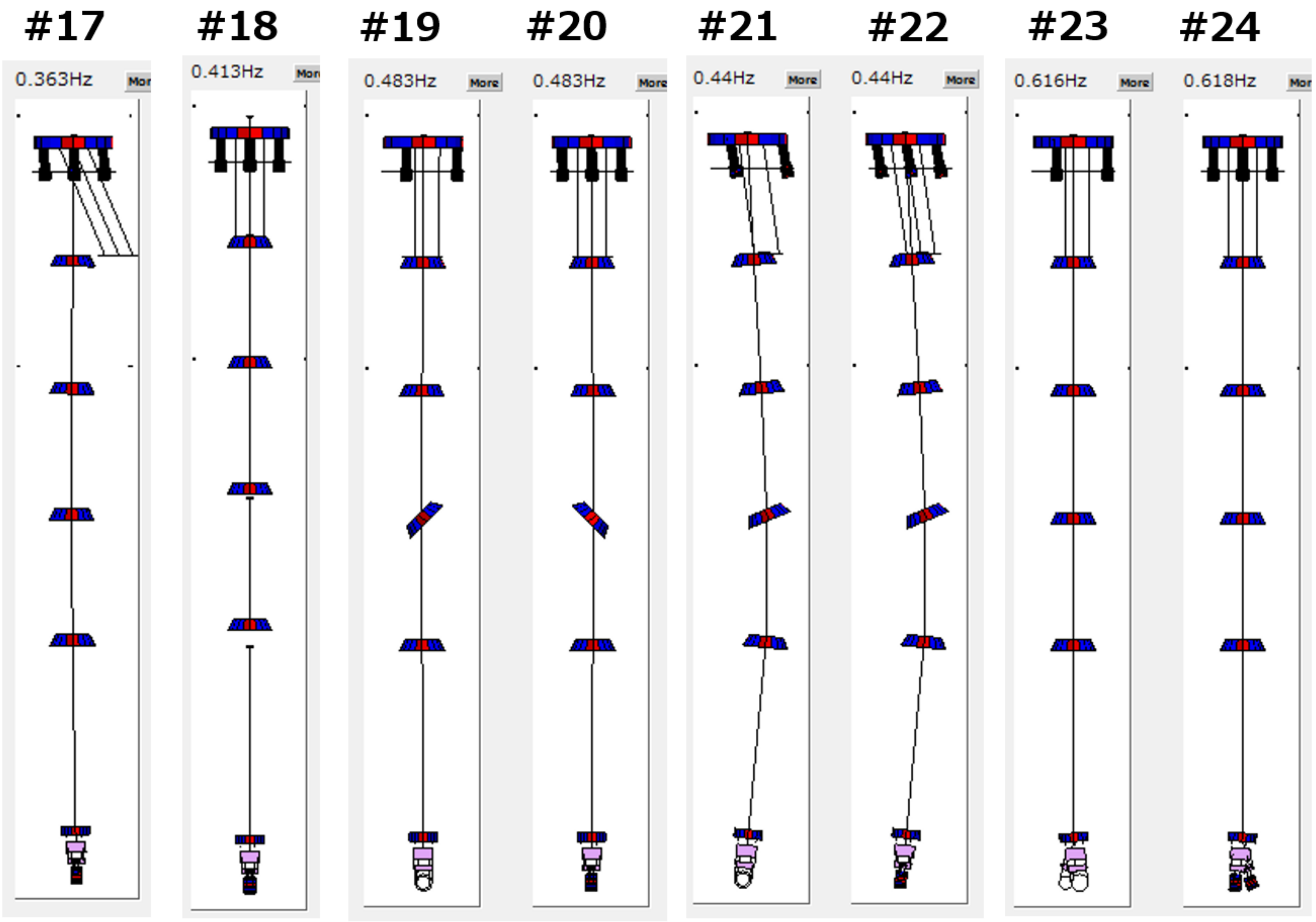


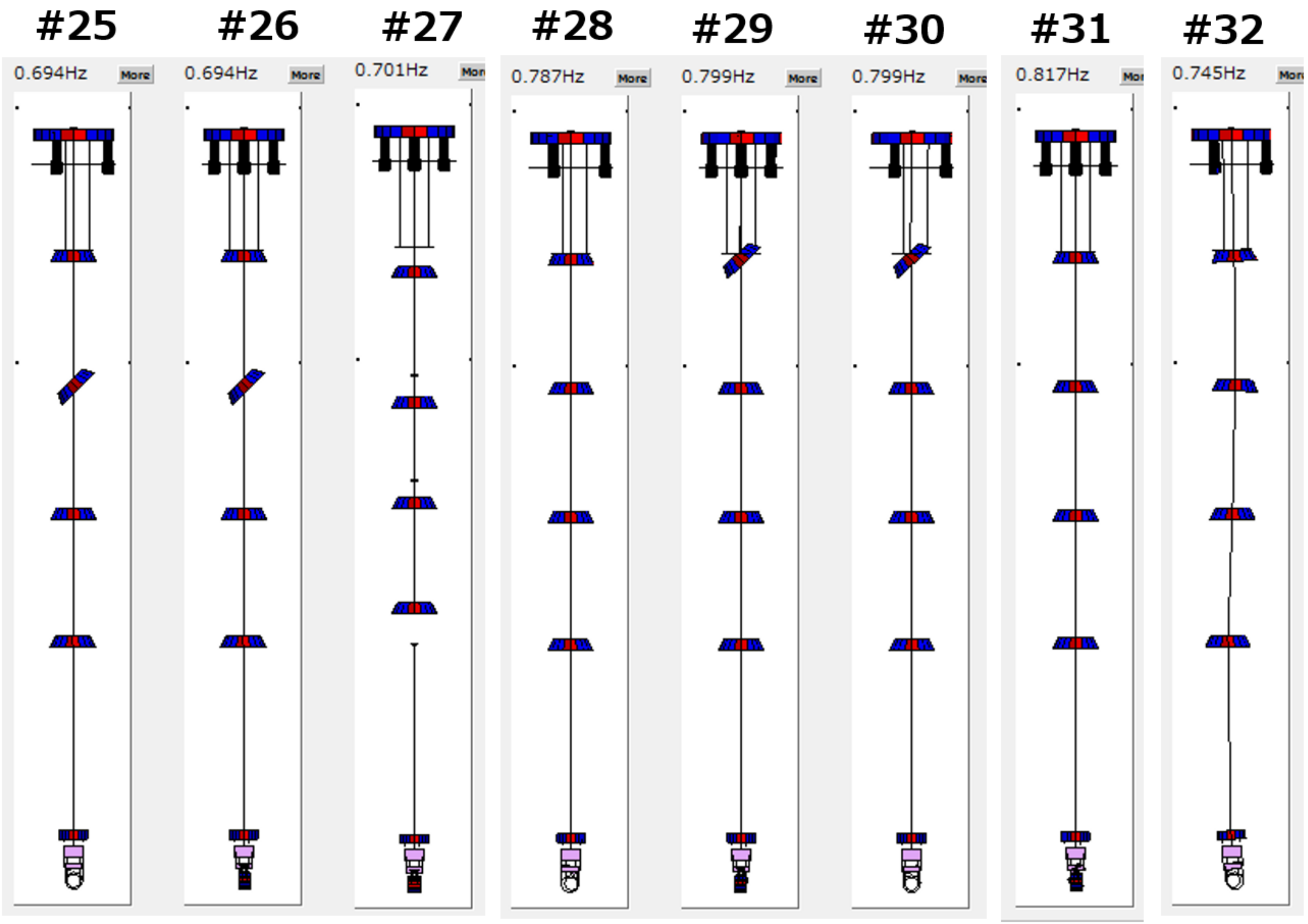
Type-A SAS,

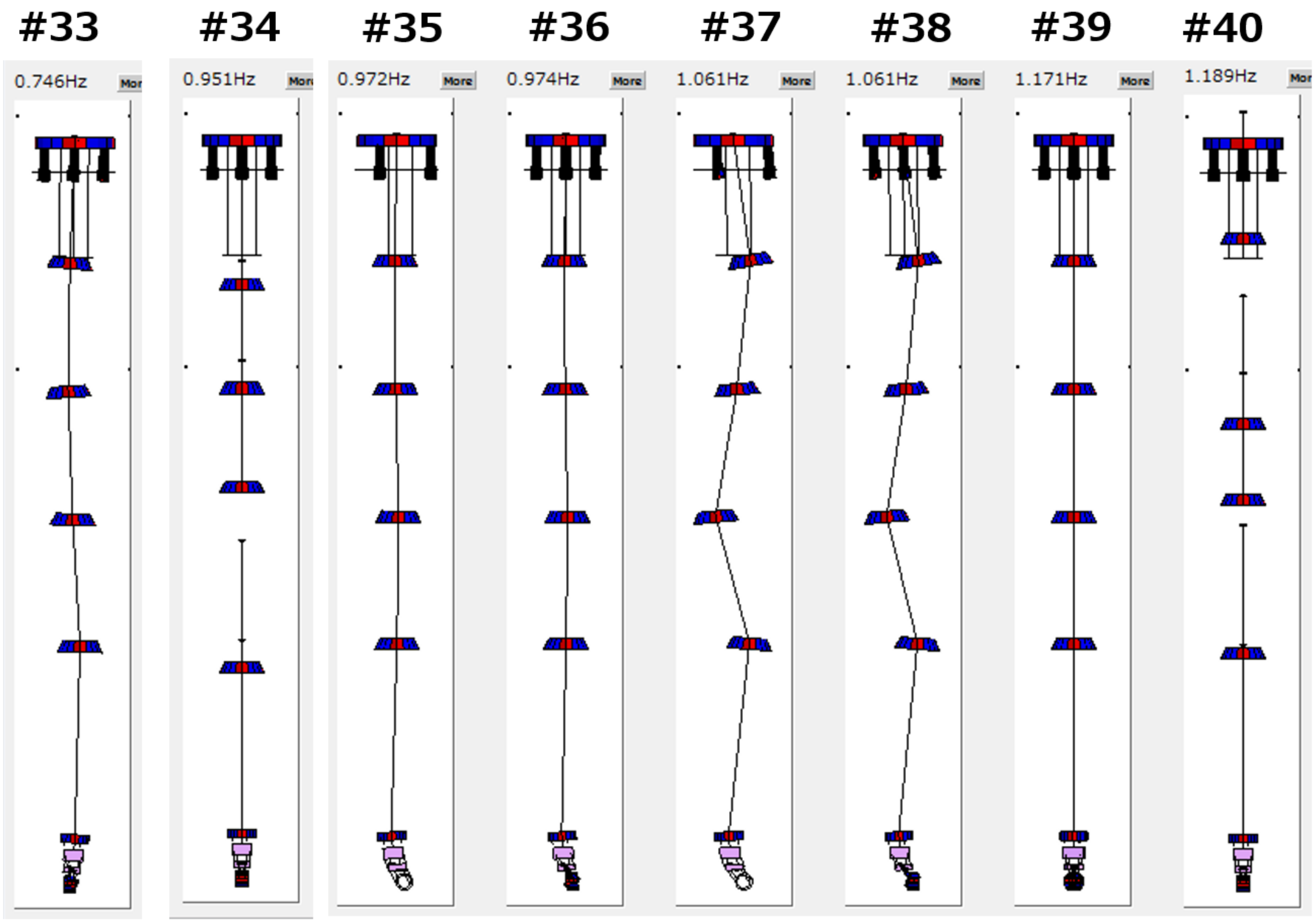
'TyrpeA180429_20K'

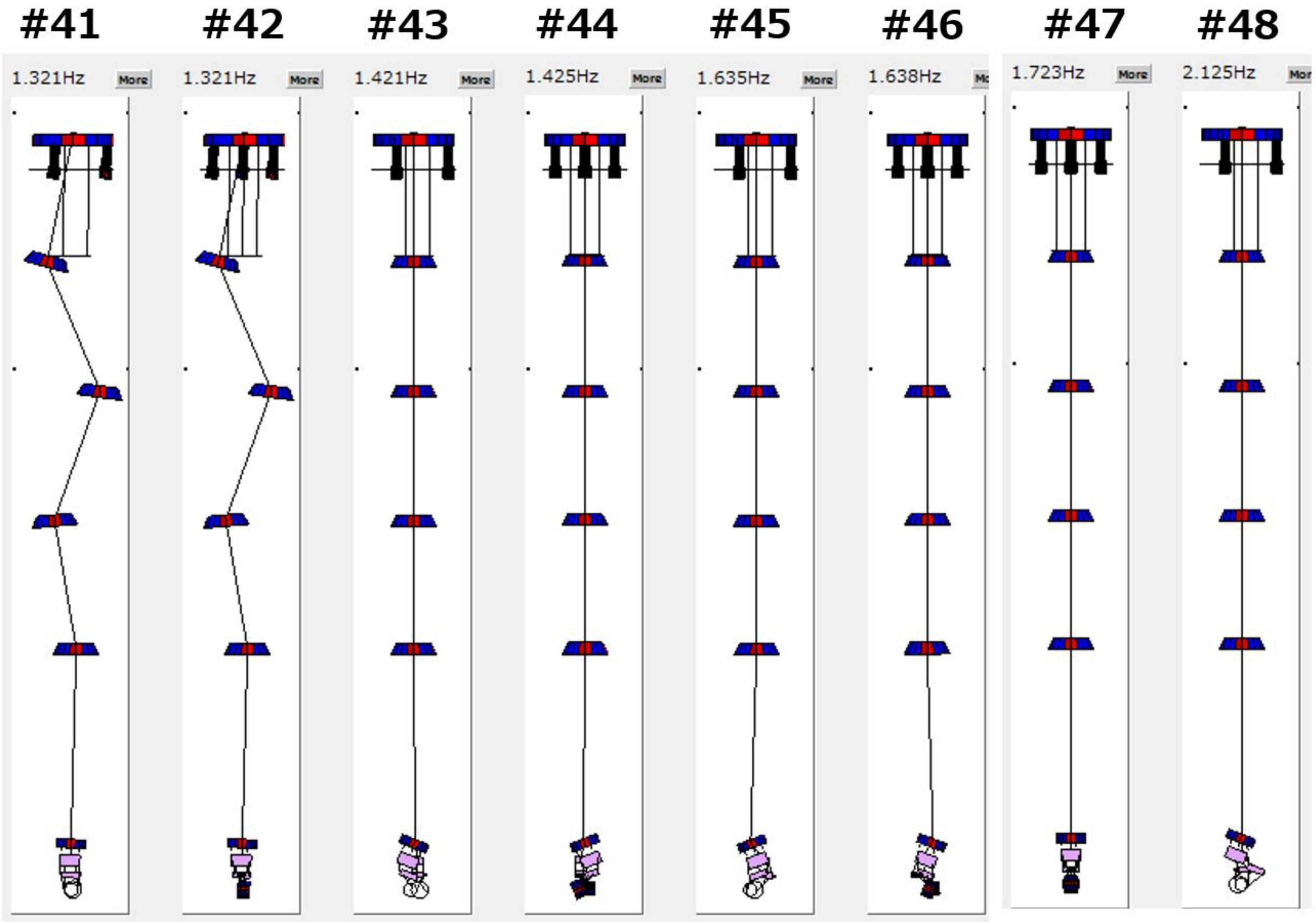
Eigen mode: 75 modes

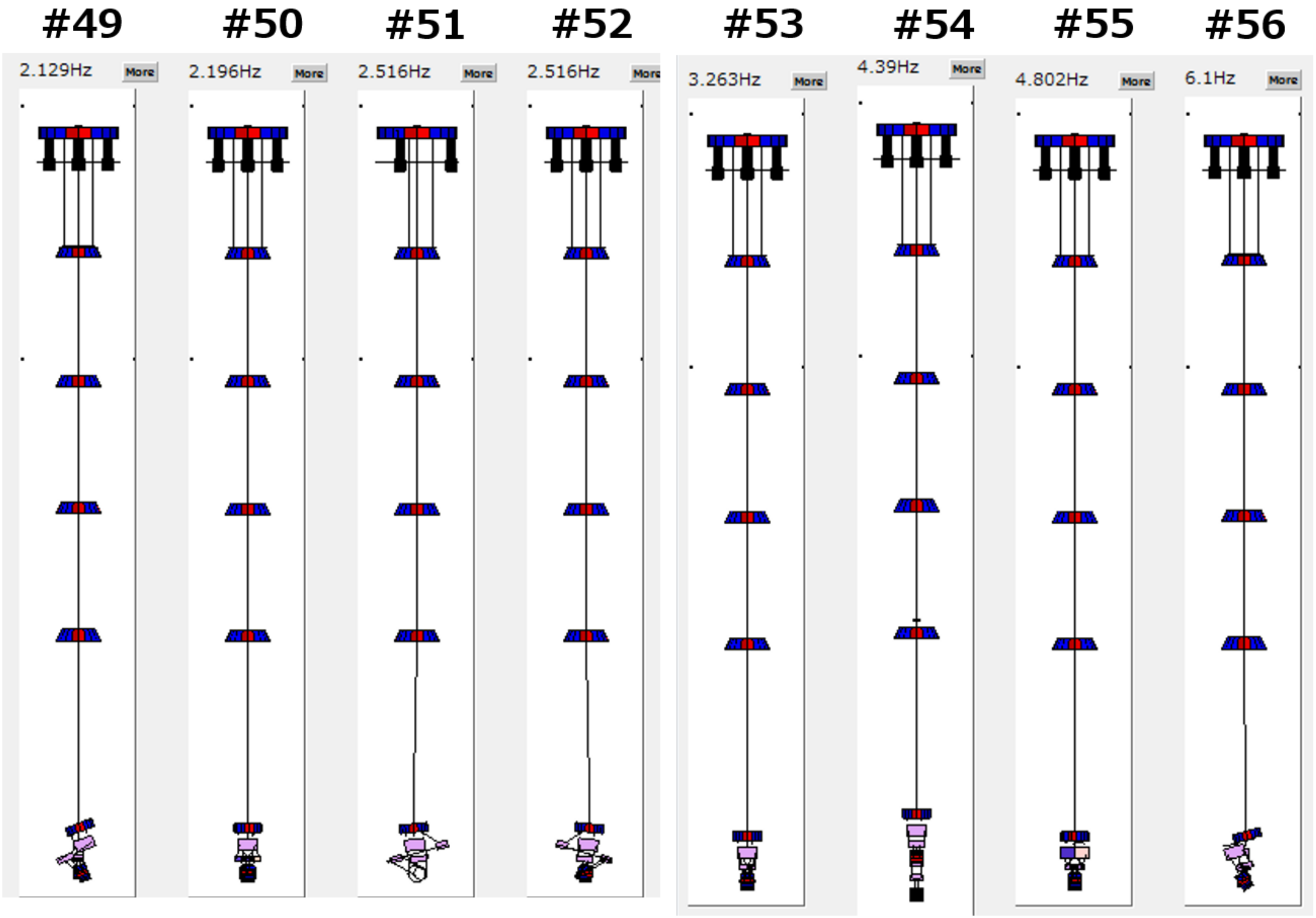

#9
0.122Hz
More
#10
0.148Hz
More
#11
0.414Hz
#12
0.203Hz
More
#13
0.203Hz
More
#14
0.28Hz
More
#15
0.359Hz
#16
0.363Hz

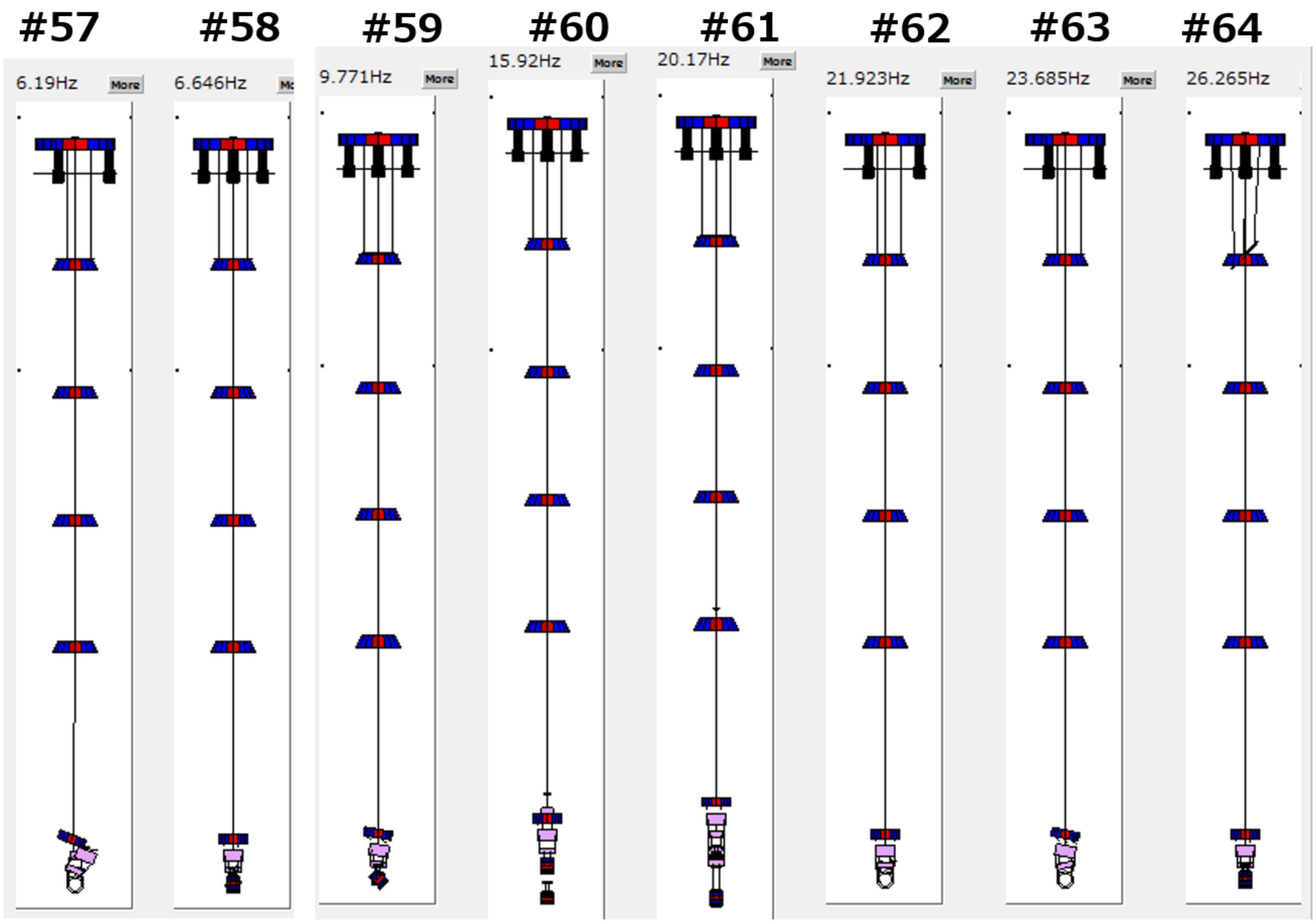

#17
#18
#19
#20
#21
#22
#23
#24
0.363Hz
0.413Hz
0.483Hz
0.483Hz
0.44Hz
0.44Hz
0.616Hz
0.618Hz

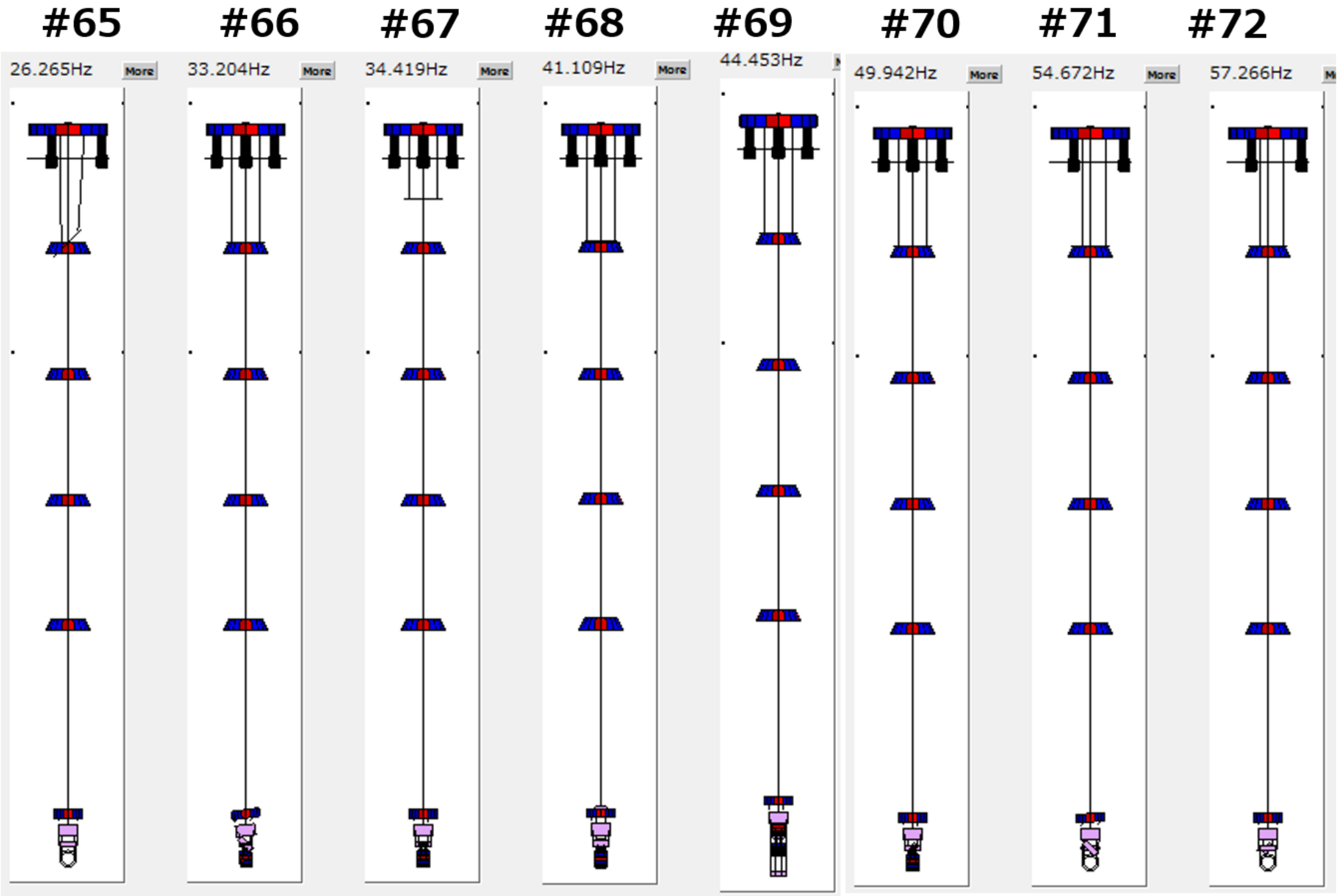

#25
0.694Hz
More
#26
0.694Hz
More
#27
0.701Hz
#28
0.787Hz
More
#29
0.799Hz
More
#30
0.799Hz
More
#31
0.817Hz
#32
0.745Hz


#33
#34
#35
#36
#37
#38
#39
#40
0.746Hz
0.951Hz
0.972Hz
0.974Hz
1.061Hz
1.061Hz
1.171Hz
1.189Hz


#41
#42
#43
#44
#45
#46
#47
#48
1.321Hz
More
1.321Hz
More
1.421Hz
More
1.425Hz
More
1.635Hz
More
1.638Hz
1.723Hz
More
2.125Hz


#49
#50
#51
#52
#53
#54
#55
#56
2.129Hz
More
2.196Hz
More
2.516Hz
More
2.516Hz
More
3.263Hz
More
4.39Hz
More
4.802Hz
More
6.1Hz
More


#57
#58
#59
#60
#61
#62
#63
#64
6.19Hz
6.646Hz
9.771Hz
15.92Hz
20.17Hz
21.923Hz
23.685Hz
26.265Hz
More


#65
#66
#67
#68
#69
#70
#71
#72
26.265Hz
More
33.204Hz
More
34.419Hz
More
41.109Hz
More
44.453Hz
49.942Hz
More
54.672Hz
More
57.266Hz

#73 #74 #75